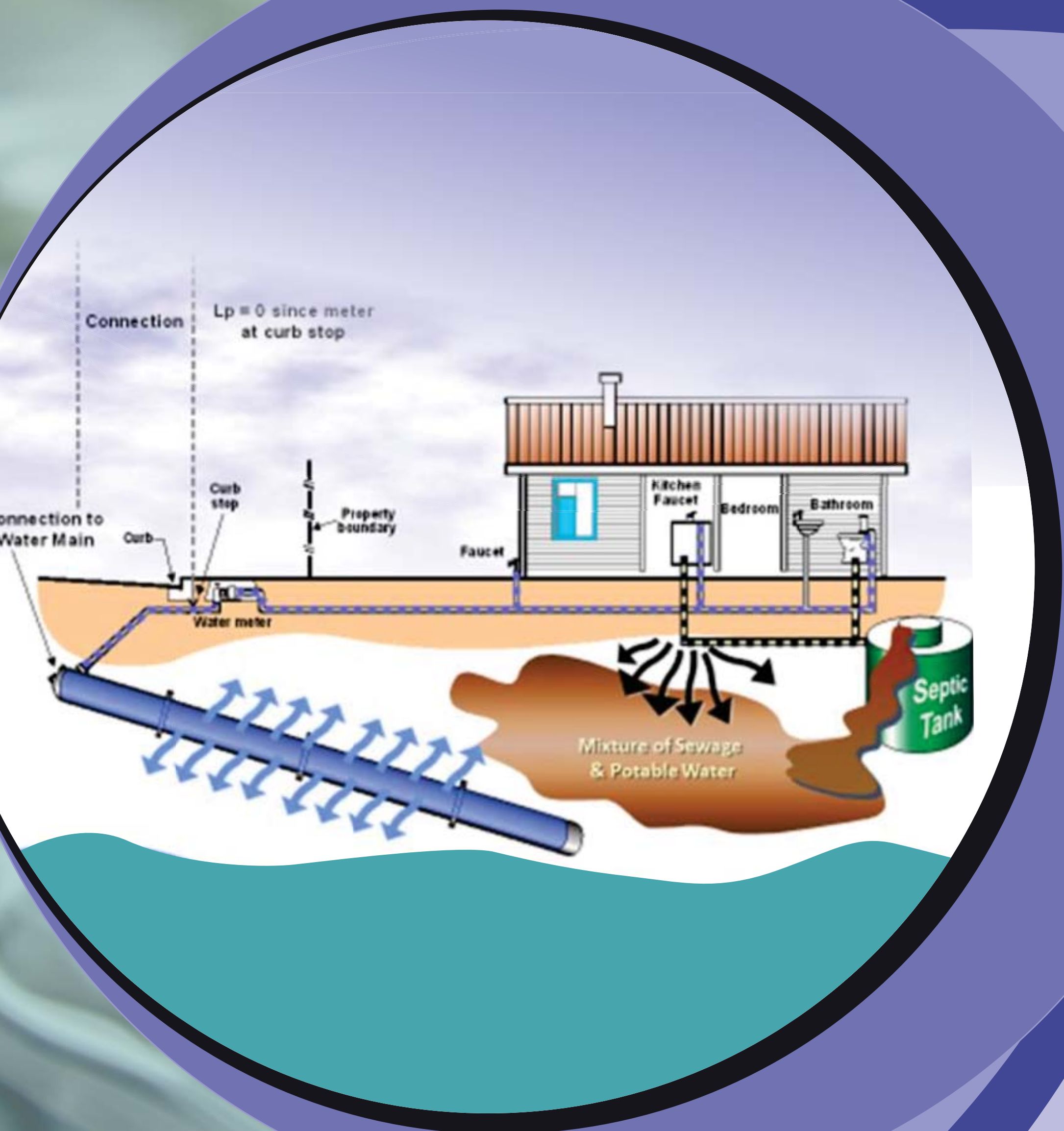
THE IMPACT OF LOWERING WATER PRESSURE ON DOMESTIC WATER DEMAND

N MEYER



WATER RESEARCH COMMISSION

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THE IMPACT OF LOWERING WATER PRESSURE ON DOMESTIC WATER DEMAND

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

Pressure management is commonly employed in water distribution systems as part of water conservation and water demand management strategies. The benefits of pressure management have been documented to include: i) reduced water leakage, ii) reduced pipe bursts, iii) extended life of water infrastructure, iv) cost savings, and v) reduced pressure dependent demand.

Pressure management refers to the procedure of reducing and regulating water pressure in a water distribution network. The pressure management options commonly used in South Africa include i) a basic pressure reducing valve (PRV) to reduce pressure to a fixed level, and ii) an advanced pressure controller that is connected to the PRV to regulate the pressure based on criteria such as the changes in flow rate or time of day.

The impact of pressure changes on consumer demand (demand downstream of the consumer meter which excludes leakage on the water distribution network) is one of the effects of pressure management that has been researched the least. In this regard this study was undertaken with the aim of determining the effect of controlled pressure adjustments on pressure dependent consumer water demand. The study objectives included:

- testing the pressure-demand relationships (demand downstream of consumer meter) in three operational water networks;
- testing the findings against results from other studies;
- summarising the findings of the study in a planning guide.

Pressure demand relationship (demand downstream of consumer meter)

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 individual consumers. All three research sites reported a positive relationship between pressure change and consumer demand, where reduced pressure resulted in reduced average consumer demand. The field exercise did however show that individual consumer demand would not always decrease with reduced pressure, and that in some cases the impact of non-technical aspects could surpass pressure-induced change for an individual consumer.

The results from the research sites were compared against the results from other studies and even though all studies showed that reduced pressure should result in reduced consumer demand, the relationship between pressure and consumer demand differed from one area to

the next. Three factors were identified which could influence the impact of pressure changes on demand, these being:

1. the presence of garden irrigation,
2. on-site leakage,
3. presence of household plumbing pressure reducing devices.

The relationship between pressure and consumer demand was expressed as the elasticity of demand to pressure which refers to the sensitivity of demand to changes in pressure (demand downstream of the consumer meter).

Garden Irrigation	A higher elasticity of demand to pressure can be expected for areas with higher garden irrigation (i.e. the demand should be impacted more through pressure reduction when there is significant garden irrigation compared to when there is no garden irrigation). The elasticity of demand to pressure ranged from <0.10 for low irrigation areas, ≈0.10-0.20 for moderate irrigation areas and >0.2 for high irrigation areas. As example, an elasticity of 0.20 would mean that the demand would decrease by 2.0% for every 10% reduction in pressure.
On-Site Leakages	A higher elasticity of demand to pressure can be expected for areas with higher on-site leakage (i.e. the demand should be impacted more through pressure reduction when there is significant on-site leakage compared to when there is no on-site leakage). The elasticity of demand to pressure ranged from ≈0.15 to ≈0.30 where on-site leakage was included and in the range of ≈0.00 to ≈0.25 where on-site leakage was excluded.
Household Plumbing PRVs	A higher elasticity of demand to pressure can be expected for some low income areas where all properties do not have household plumbing PRVs (i.e. the indoor demand should be impacted more through pressure reduction when there are no household plumbing PRVs compared to when each house is fitted with plumbing PRVs). This finding suggests that indoor consumer demand (excluding on-site leakage) in some suburban areas may not reduce notably with 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.

Minimum pressure requirements

When pressure management is considered, the minimum acceptable pressure for the area should also be considered. The CSIR Red Book recommends a minimum pressure during peak demand of 24 m for residential areas in South Africa. The actual achievable minimum pressure will differ from one area to the next and from one municipality to the next. Under normal circumstances for an average residential area, 24 m at the critical point should be sufficient. For low income areas with minimum garden irrigation and few water end-use points, the minimum acceptable pressure may be lower than 24 m, and for some high income areas the minimum acceptable pressure may be higher than 24 m. A theoretical minimum pressure of 10 m is required to ensure effective operation of some household appliances.

During drought conditions some municipalities may also consider lowering the minimum pressure requirements in order to achieve additional water savings. In 2018 the City of Cape Town experienced a drought and reduced the minimum pressure at critical points to 10-15 m for 4 hours in the morning, and 5-10 m for the remainder of the day (with the use of advanced pressure controllers).

Planning guide

A planning guide that can used by municipalities to estimate the approximate impact of a pressure management initiative was prepared from the results obtained in this study. It should be noted that the guideline presented below will not necessarily be accurate for every area and certain additional factors may influence the results. These additional factors can include, but not be limited to: changes in weather, changes in water tariffs, large fluctuation in pressure in a DMA, intermittent supply in parts or all of the DMA, unusual pressure-leakage relationship or unusual pressure-demand relationship for a specific DMA. When a more accurate assessment of the potential savings from pressure management is required, it is recommended to obtain flow and pressure logging data for the DMA and to analyse the data with one of the software packages available. It should also be noted that the guideline below was prepared with available data from a limited number of sites and as more data becomes available in future it may be possible to improve the guideline.

Step 1 – Assess potential for pressure management

The scope for pressure management in each DMA should be assessed. The minimum acceptable pressure in each DMA should be determined and this will vary from municipality to municipality and from one DMA to the next. The existing pressure can either be measured with the use of pressure gauges / pressure data recorders or the pressure can be estimated with the use of a hydraulic model. Once the existing pressures are known the scope to reduce pressure can be determined for each DMA.

Step 2 – Assess potential impact of pressure management on consumer demand and DMA input volume

The reduction in residential consumer demand (demand downstream of consumer meter) can be estimated using the guideline below. It should be noted that the figures shown below should only be used as a guide. The pressure-demand relationship will vary from one area to the next due to differences in consumer profiles, demand profiles and leakage levels inside houses.

Reduction in Consumer Demand from Pressure Management

MNF / AVG	Expected On-Site Leakage Level	Garden Irrigation Level	% Reduction in residential consumer demand for 10% reduction in pressure	
			Min Factor	Max Factor
< 20%	Low	Low to Moderate	0%	1%
20% - 40%	Medium	Low to Moderate	1%	2%
> 40%	High	Low to Moderate	1%	3%
< 20%	Low	High	1%	2%
20% - 40%	Medium	High	2%	3%
> 40%	High	High	2%	4%

Notes:

1. Consumer demand mentioned above refers to actual consumer demand downstream of the consumer connection.
2. The MNF/AVG refers to the ratio of minimum night flow (MNF) over average logged flow. This ratio is used as one of the indicators of the leakage level in a system.
3. The figures shown above refer to residential consumers.

The reduction in input volume for a residential DMA can be estimated using the guideline below. Where a more accurate assessment of the potential savings from pressure management is required, it is recommended to obtain flow and pressure logging data for the DMA and to analyse the data with one of the software packages available (discussed in Section 7 of report).

Reduction in Input Volume from Pressure Management

MNF / AVG	Expected Water Network Leakage Level	Garden Irrigation Level	% Reduction in DMA input volume for 10% reduction in pressure	
			Min Factor	Max Factor
< 20%	Low	Low to Moderate	1.5%	3%
20%-40%	Medium	Low to Moderate	2%	4%
> 40%	High	Low to Moderate	3%	6%
< 20%	Low	High	2%	4%
20%-40%	Medium	High	3%	5%
> 40%	High	High	3%	7%

Note:

The figures above refer to residential DMAs.

The estimated reduction in input volume from pressure management includes the estimated reduction in consumer demand due to pressure management.

Conclusion

The basic planning guide presented above can be used by municipalities to estimate the potential reduction in consumer demand and the potential reduction in DMA input volume from a pressure management initiative. A pressure management exercise should generally result in a reduction of the total input volume as well as a reduction in average consumer demand although the impact on consumer demand can in some cases be very low to negligible.

The following factors should be considered when estimating the impact of a specific pressure management initiative:

- The higher the scope for pressure reduction, the higher the expected impact on consumer water demand and input volume will be.
- In areas where the on-site leakage is high, pressure management will have a larger effect on reducing consumer demand compared to areas with low on-site leakage (demand downstream of consumer meter).
- The consumer demand should be impacted more through pressure reduction when there is significant garden irrigation compared to when there is no garden irrigation (demand downstream of consumer meter).
- Higher savings should be achievable through pressure management in areas with high water network leakage compared to areas with low network leakage.

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d	day
h	pressure head (metres head)
kL	kilolitre
kL/d	kilolitre per day
L	litres
L/d	litres per day
m	metres
masl	metres above sea level
mm	millimetres
Q	flow rate
Q_{dem}	consumer water demand
Q_{dem-c1}	average demand for all individual consumers in used dataset
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)
CP	critical point
DMA	district metered area
GL	ground level
GSM	global system for mobile communications
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
WRC	Water Research Commission

TERMINOLOGY

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).
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.
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.
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).
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 water distribution system 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.
DMA Discreteness	A DMA is considered to be discrete if no open cross-boundary connections with adjacent DMAs exist.
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).
End-use	Jacobs (2004) defined end-use as a device or fixture where water is released from the pressurised water supply system to atmosphere.
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).
Pressure Management	Pressure management refers to the procedure of reducing and regulating water pressure in a water distribution network.
Pressure Reducing Valve (PRV)	A pressure reducing valve (PRV) is a device used to lower water pressure to a set pressure.
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 INTRODUCTION

1.1 Background

Pressure management is commonly employed as part of water conservation and water demand management strategies in water distribution systems. The benefits of pressure management have been well documented to include: reduced water leakage, extended life of water infrastructure, reduced pipe bursts, cost savings and reduced pressure dependent demand.

The impact of pressure changes on consumer demand (demand downstream of the consumer meter which excludes leakage on the water distribution network) is one of the effects of pressure management that has been researched the least. In this regard this study was undertaken with the aim of determining the effect of controlled pressure adjustments on pressure dependent consumer water demand. The study objectives included:

- testing the pressure-demand relationships (demand downstream of consumer meter) in three operational water networks;
- testing the findings against results from other studies;
- summarising the findings of the study in a planning guide.

This document should be read in conjunction with the following publications:

Presmac Software and user guide (WRC Report TT 152/01). The Presmac software was developed by the WRC and can be used to assess the theoretical potential water savings from implementing pressure management.

Sanflow Software and user guide (WRC Report TT 109/99). The Sanflow software was developed by the WRC and can be used to analyse minimum night flows.

Leakage Reduction through Pressure Management: Concepts and Case Studies, WRC Report TT 186/02.

Report on the interpretation of logging results as a water network problem solving tool (WRC Report TT 737/17). This report provides a guideline for municipalities to identify and resolve a number of different operational problems through logging of pressures and flows and the interpretation of those logging results.

1.2 Study Methodology

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 District Meter Areas (DMAs) were identified based on selection criteria. The three DMAs were located in the City of Tshwane. 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 were analysed by establishing the pressure-demand relationship for each test DMA, as well as for individual consumers.

> Terminology:
>
> The term district metered area (DMA) was adopted from the UK water industry and refers to a discrete portion of the water distribution network 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.

1.3 Pressure Management Methods

Pressure management is the procedure of lowering and regulating water pressure in a water distribution systems to minimum acceptable levels that are in line with national and municipal guidelines. The pressure management methods commonly used in South Africa are summarised below.

1.3.1 Fixed outlet pressure control

Fixed outlet control is the most common form of pressure control 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 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.

1.3.2 Advanced pressure control (smart pressure control)

Water distribution systems 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 will 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 advanced 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 will typically be set to reduce off-peak pressures. 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 when, for example, 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 will normally provide larger water savings than time-modulated control but the flow-modulated option will typically be 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.

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.

1.4 Pressure Management Benefits

Pressure management has been documented to be fundamental in water conservation strategies. 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 will result in reduced water leakage (Gebhardt, 1975, McKenzie et al., 2004, Mckenzie and Wegelin, 2005). A number of software packages have been developed to analyse the potential water savings from implementing different forms of pressure management (i.e. Presmac developed by the WRC (McKenzie, 2001), and Prescalc (Thornton and Lambert, 2005).
Reduced burst pipes	Studies by Gomes et al. (2011) and Martínez-Codina et al. (2015) confirmed that reduced pressure will result in reduced burst pipes.
Extended asset life	With reduced burst pipes the water distribution network is likely to last longer. Lambert and Thorton (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) that showed that pressure management can result in reduced pumping costs, reduced sewerage treatment costs as well as the associated reduction in CO_2 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).
Reduced pressure dependent demand.	The impact of pressure on demand (demand downstream of the consumer meter which excludes leakage on the water distribution network) is one of the benefits of pressure management that has been researched the least and is also the focus of this study and discussed on the next page.

1.5 Pressure Demand Relationship

Some of the documented studies on the pressure-demand relationship (demand downstream of the consumer meter) is summarised below:

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 (Qdem) was expressed as Equation (1). $$Q_{dem} = C\, h^{\beta} \qquad (1)$$ Qdem = consumer water demand; C = constant coefficient (dimensionless); h = pressure head; β = elasticity of demand to pressure (dimensionless). 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).
Bamezai & Lessick (2003) in USA 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 as shown in Equation 1), and a decrease of 4.1% was reported for properties with larger gardens (equivalent to elasticity of demand to pressure of 0.24).
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.

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.

1.6 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 1.

Table 1: 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 water network 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 CASE STUDY SELECTION

2.1 Description of Study Sites

The data analysed in this study were collected through three full-scale field experiments, conducted in three District Metered Areas (DMAs) which form part of an operational water distribution system. All three DMAs were located in the City of Tshwane. Tshwane is located in the Gauteng province in a summer rainfall region with relatively high summer temperatures and moderately cold, dry winters.

2.2 Study Implementation Procedure

The following procedure was used to implement the study:

Step 1: Planning of field experiments.	Field experiments were planned to obtain pressure and flow data from an operational water network 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.
Step 2: Selection of case study areas.	Three DMAs in three different residential areas were identified, based on selection criteria referred to in Section 2.3. 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.
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 were 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.

2.3 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 DMAs had to be confirmed as discrete.
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 critical point (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.

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

Three DMAs meeting the above criteria were identified and are summarised in Table 2.

Table 2: Characteristics of selected DMAs (adapted from Meyer et al., 2018)

Description	DMA1	DMA 2	DMA 3
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 (masl)	1460	1275	1475
Critical Point (CP) elevation (masl)	1462	1280	1480
Lowest geographical point elevation (masl)	1424	1218	1440

3 DATA COLLECTION

3.1 What is Data Recording / 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. 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). A description on the procedure and equipment used for data recording/ data logging is provided in WRC Report TT 737/17.

3.2 Data Recording

A summary of the data recording undertaken in this study is shown in Table 3.

Table 3: Summary of data recording points

Description	DMA1	DMA2	DMA3
Flow at DMA Bulk meter	200 mm diameter Sensus WPD Meter	200 mm diameter Sensus WPD Meter	150 mm diameter Sensus WPD by-pass Meter
Pressure at PRV outlet	200 mm diameter Singer PRV	150 mm diameter Bermad PRV	150 mm 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

Note: Flow data recorders were programmed for time-based recording using 15-minute intervals. The volumetric recording sensitivity was 0.5 L and 1000 L (1 kL) per pulse for the consumer meters and DMA bulk meters respectively.

3.3 Sample size for consumer flow recording and selection of properties

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 Zone2 and 32 for Zone3. 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 zones 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 small, with data for 1.6%, 0.6% and 3.9% of all consumers in DMA1, DMA2 and DMA3 respectively being recorded. The consumers were selected to ensure a relatively even distribution between three demand categories and three pressure categories (refer to **Table 4**). Consumers in the study sample were purposefully not informed about the field experiments and the research study in order to minimise consumer bias.

Table 4: Selection of consumers for flow recording

DMA	Ground level (GL) in m above sea level	No. of consumers with Average Annual Daily Demand (AADD) kL/d		
		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
	1250 m < GL < 1270 m	9	4	0
	GL ≥ 1470 m	5	0	1
DMA 3 (32 data recorders)	GL ≤ 1455 m	1	4	8
	1455 m < GL < 1465 m	1	3	3
	GL ≥ 1465 m	4	4	4

3.4 Data Recorder Installation Procedure

Photos depicting the data recorder installations are provided in Figure 1 to Figure 3. Information on the procedure and equipment used for data recording/ data logging is provided in WRC Report TT 737/17.

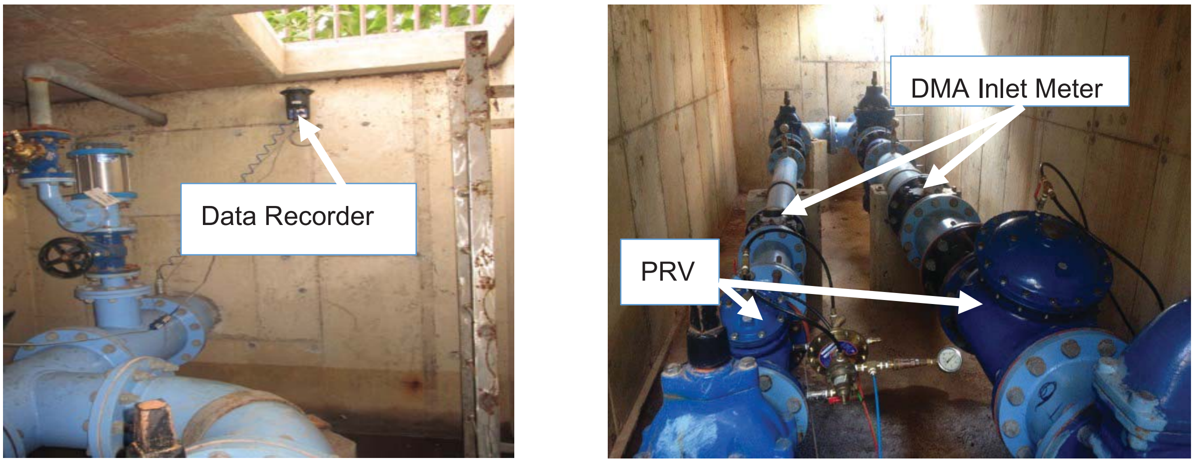

Figure 1: Typical data recorder installation at PRV

Figure 2: Typical data recorder installation at critical point

Temporary removal of water meter

Connecting reed switch to data recorder

Inserting data recorder into meter box

Re-installation of water meter (hiding the data recorder underneath)

Figure 3: Installation of data recorders at consumer meters

4 CASE STUDY DATA

4.1 Case Study 1

The characteristics of DMA 1 is summarised in **Table 5**.

Table 5: DMA 1: Characteristics

DMA Characteristic	DMA1
Average income of consumers	High
Total plots	1201
Occupied plots	1087
Residential plots (expressed as a number and as a percentage of the occupied plots)	1025 (94%)
Total length of water pipes (km)	±24
PRV elevation (masl)	1460
Critical Point (CP) elevation (masl)	1462
Lowest geographical point elevation (masl)	1424

4.1.1 DMA input flow and pressure data

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 logging data are summarised in **Table 6** and graphically shown in **Figure 4**.

Table 6: DMA 1: Summary of logging data

	Period 1	Period 2	Period 3	Period 4	Period 5
Start Date	**2016/05/06**	**2016/05/24**	**2016/06/07**	**2016/06/23**	**2016/07/07**
End Date	**2016/05/18**	**2016/06/05**	**2016/06/19**	**2016/07/05**	**2016/07/20**
Average PRV D/S Pressure (m)	54	46	33	27	23
Average CP Pressure (m)	52	45	32	26	22
Average Zone Inflow (m^3/hr)	72	69	60	64	65
Average MNF (m^3/hr)	27	25	22	23	21

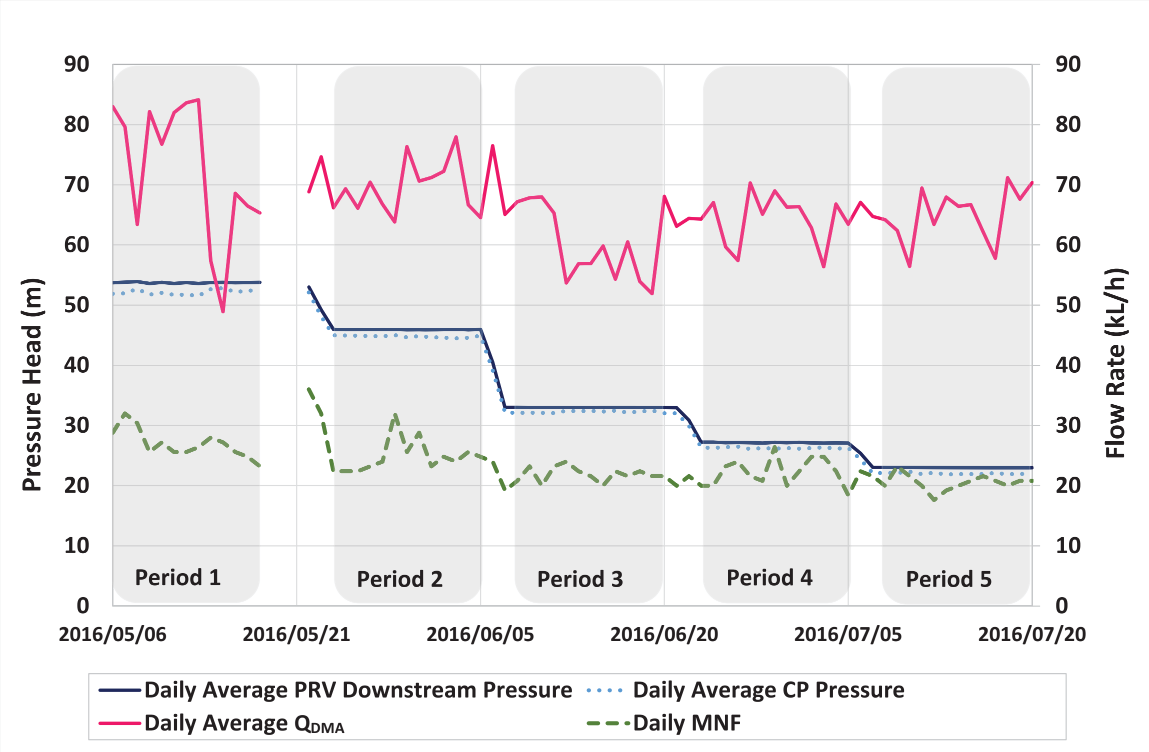

Figure 4: DMA1 time series pressure and flow profile (adapted from Meyer et al., 2018)

Figure 4 show that the PRV downstream pressure and critical point pressure reduced, with each test period. The DMA inflow (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 minimum night flow (MNF) in DMA1 reduced with reduced pressure.

Terminology	Q_{DMA} refers to the DMA inlet flow rate, recorded at the DMA inlet meter. Minimum night flow (MNF) is the minimum flow recorded over the logged time period, usually daily between 1am and 3am. For a residential area a constant minimum night flow is normally a clear indication of leakage.

In Figure 5 the average DMA inflow (Q_{DMA}) and minimum night flow (MNF) were calculated for each test period and plotted against the corresponding average pressure head in the DMA, for the same period. The MNF represents the combined physical leakage on the water network and consumer level, as well as a small component of legitimate night usage at consumers. The residential demand component (Q_{dem}) in Figure 5 was estimated using Equation (2).

$$Q_{dem} = (\text{Average } Q_{DMA} - \text{ MNF}) + \text{Legitimate Night Usage} \qquad (2)$$

Q_{dem} represents the actual demand component in a largely residential DMA which excludes physical leakage in the water network and leakage at consumers.

The legitimate night usage in a residential DMA can be calculated but is expected to be relatively small and mainly due to toilet use (McKenzie, 1999), which is also pressure independent (refer to Section 1.6). The legitimate night usage component in residential DMAs should therefore remain constant under pressure changes and should not contribute notably to any variance in Q_{dem} in Equation 2. In this regard, the legitimate night usage term in Equation 2 can be left out. Equation 2 should preferably not be used if there is a significant difference between the general day and night pressures in a DMA (less than 10 m difference was considered acceptable) since that would imply that the leakage rate (MNF) will not be relatively constant.

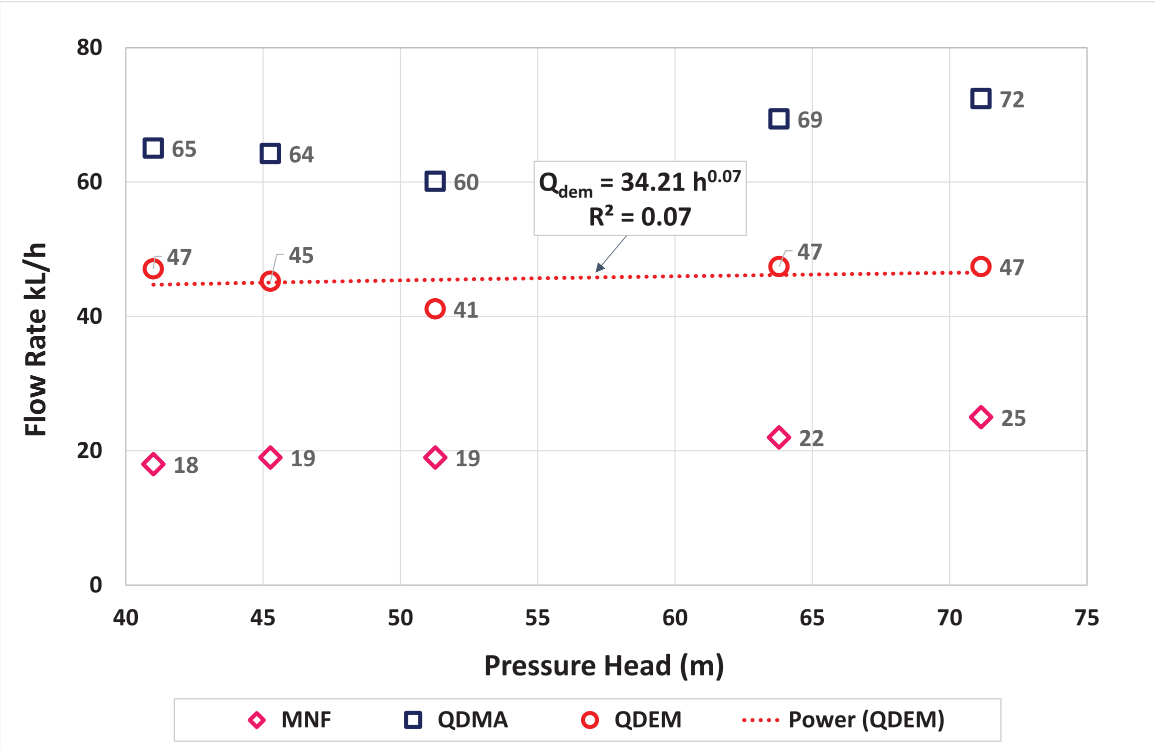

Figure 5: DMA1 Q_{DMA}, MNF and Q_{dem} versus pressure head

Figure 5 show that DMA inflow (Q_{DMA}), minimum night flow (MNF) and Q_{dem} generally reduced with reduced pressure. Q_{dem} refers to the actual demand component for the DMA as a whole which excludes physical leakage in the water network and leakage at consumers. The impact of pressure changes on Q_{dem} does however seem to be small. A trend line based on a power regression equation was fitted to the Q_{dem} values. The trend line indicate the approximate pressure-demand relationship and do not take into account the potential role of other external factors on consumer demand.

4.1.2 DMA1 consumer flow data

In order to compare the flow data for individual consumers with the flow data for the DMA as a whole the average individual consumer water demand in each period was calculated and plotted against the corresponding pressure head, as shown in Figure 6. The average consumer demand was calculated using two datasets for each DMA, as summarised below:

Q_{dem-c1}	Average demand for all individual logged consumers in DMA.
Q_{dem-c3}	Average demand for individual logged consumers in DMA which excluded consumers where medium or high MNF was recorded (i.e. excluding consumers with on-site leakage). The demand for consumers without on-site leakage was separately analysed in order to assess how the general pressure-demand relationship will change if there is no on-site leakage.

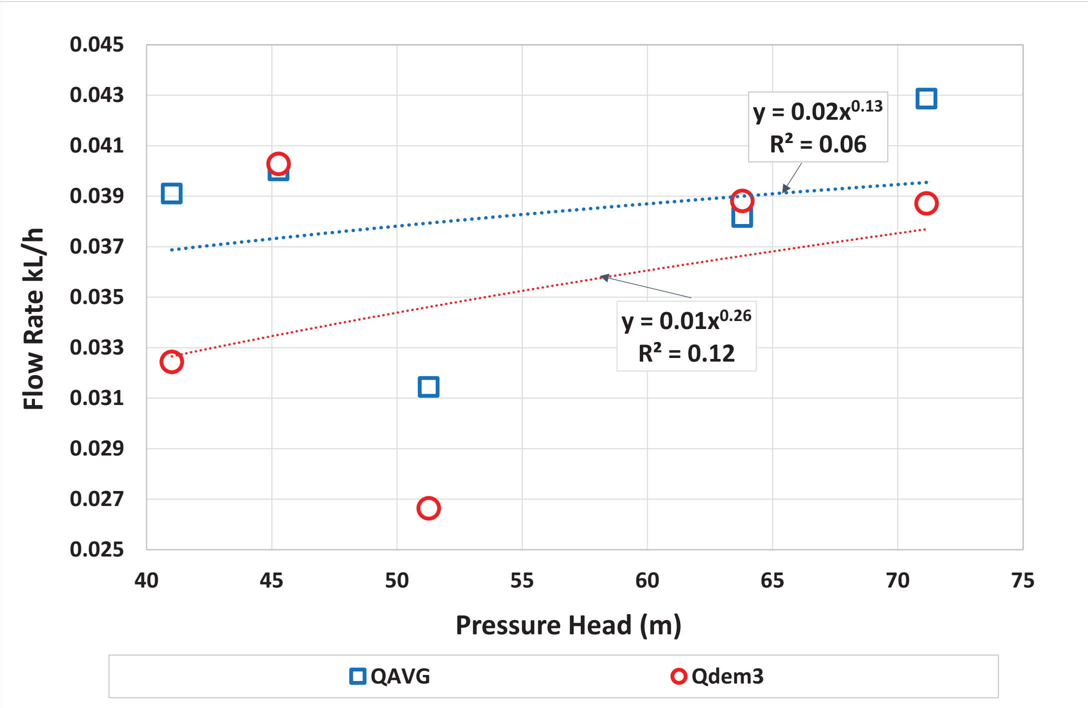

Figure 6: DMA1 $Q_{dem\ c1}$ and $Q_{dem\ c3}$ versus pressure head

Figure 6 show that $Q_{dem\ c1}$ and $Q_{dem\ c3}$ generally reduced with reduced pressure. Trend lines based on a power regression equation were fitted, however it is noted in Section 5 that the sample size for individual consumer flow recording in DMA1 was considered to be too small to draw accurate conclusions from the equations shown in Figure 6.

4.2 Case Study 2

The characteristics of DMA 2 is summarised in **Table 7**.

Table 7: DMA 2: Characteristics

DMA Characteristic	
Geographical location in City of Tshwane	North West
Average income of consumers	Low
Total plots	4683
Occupied plots	4558
Residential plots (expressed as a number and as a percentage of the occupied plots)	4547 (98%)
Total length of water pipes (km)	±45
PRV elevation (masl)	1275
Critical Point (CP) elevation (masl)	1280
Lowest geographical point elevation (masl)	1218

4.2.1 DMA2 input flow and pressure data

The field exercise was undertaken from 27 October 2016 to 31 January 2017. The PRV was fitted with an electronic controller with remote GSM programming functionality. The required pressure adjustments were done remotely with the use of the electronic controller. A summary of the logging data is presented in **Table 8** and graphically shown in Figures 7 and 8.

Table 8: DMA 2: Summary of logging data

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Start Date	2016/10/27	2016/11/11	2016/11/25	2016/12/23	2017/01/11	2017/01/25
End Date	2016/11/08	2016/11/23	2016/12/07	2017/01/04	2017/01/23	2017/01/31
Average PRV D/S Pressure (m)	50	41	30	26	21	17
Average CP Pressure (m)	43	34	24	19	15	11
Average Zone Inflow (m^3/hr)	122	105	103	98	94	84
Average Zone MNF (m^3/hr)	89	72	68	64	57	51

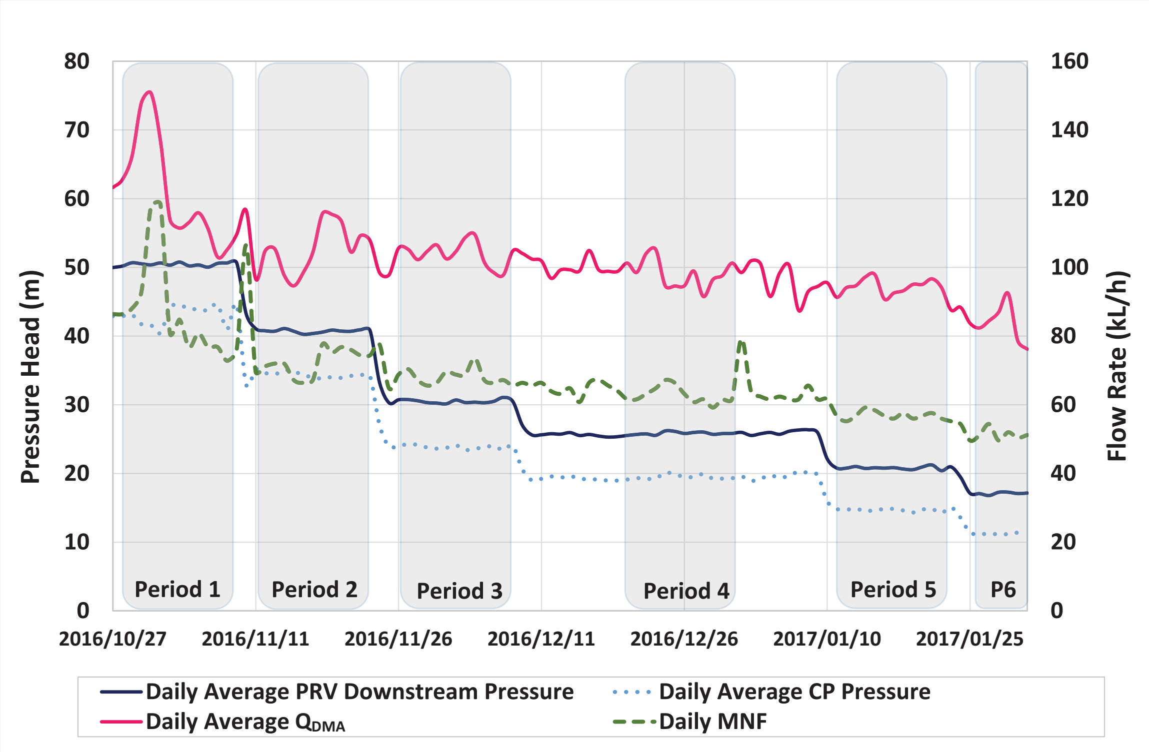

Figure 7: DMA2 time series pressure and flow profile (adapted from Meyer et al., 2018)

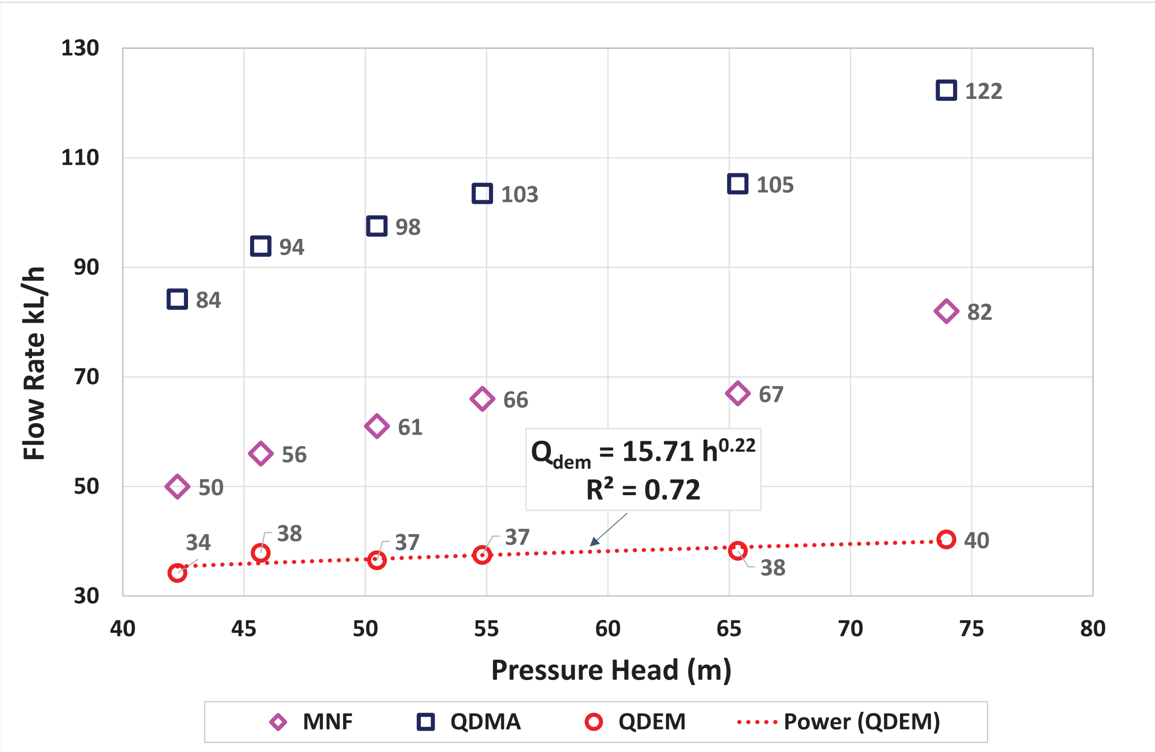

Figure 8: DMA2 Q_{DMA}, MNF and Q_{dem} versus pressure head

Figures 7 and 8 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. A trend line based on a power regression equation was fitted to the Q_{dem} values in Figure 8. The trend line indicate the approximate pressure-demand relationship for the particular case in question and do not take into account the potential role of other external factors on consumer demand.

4.2.2 DMA2 consumer flow data

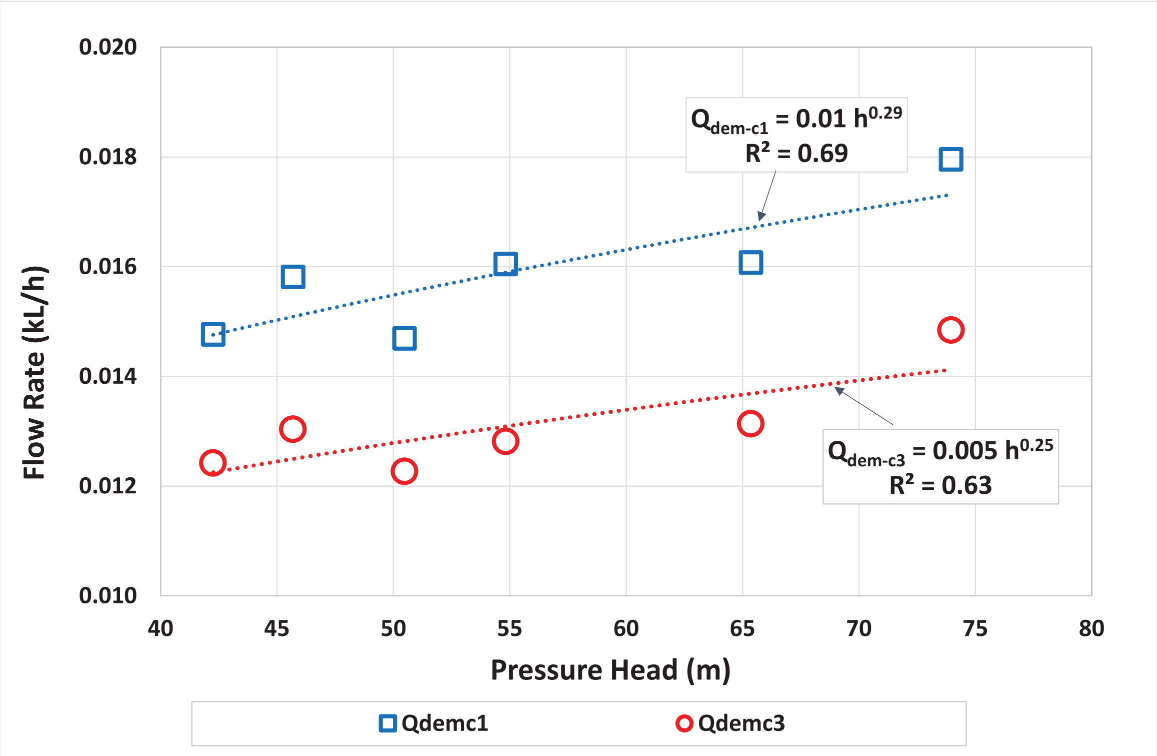

Figure 9: DMA2 $Q_{dem\ c1}$ and $Q_{dem\ c3}$ versus pressure head

Figure 9 show that $Q_{dem\ c1}$ and $Q_{dem\ c3}$ reduced with reduced pressure. Trend lines based on a power regression equation were fitted. The trend line for $Q_{dem\ c1}$ (all logged consumers) differed marginally from the trend line for $Q_{dem\ c3}$ (consumers with on-site leakage excluded) which suggest that on-site leakage was not the only driving force behind the pressure-demand relationship for DMA2. DMA2 is a formal low-income area and few random checks revealed that a number of properties in this area were not equipped with hot water geysers and therefore these properties will not be equipped with household plumbing PRVs. This observation is relevant to the pressure-demand relationship for DMA2 and is discussed in Section 6.

4.3 Case Study 3

The characteristics of DMA 3 is summarised in **Table 9**.

Table 9: DMA 3: Characteristics

DMA Characteristic	
Geographical location in City of Tshwane	West
Average income of consumers	Medium
Total plots	923
Occupied plots	866
Residential plots (expressed as a number and as a percentage of the occupied plots)	827 (95%)
Total length of water pipes (km)	18
PRV elevation (masl)	1475
Critical Point (CP) elevation (masl)	1480
Lowest geographical point elevation (masl)	1440

4.3.1 DMA 3 input flow and pressure data

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 logging data is summarised in **Table** 10 and graphically shown in Figures 10 and 11.

Table 10: DMA 3: Summary of logging data

Start Date	2017/05/10	2017/05/25	2017/06/08	2017/06/24	2017/07/20	2017/08/01
End Date	**2017/05/23**	**2017/06/06**	**2017/06/21**	**2017/07/07**	**2017/07/30**	**2017/08/06**
Average PRV D/S Pressure (m)	59.95	48.97	36.95	24.81	20.95	14.90
Average CP Pressure (m)	65.18	54.01	43.12	30.87	27.07	21.16
Average Zone Inflow (m^3/hr)	100.03	93.00	83.25	78.75	79.30	77.20
Average Zone MNF (m^3/hr)	52.00	46.00	37.00	33.00	33.00	32.00

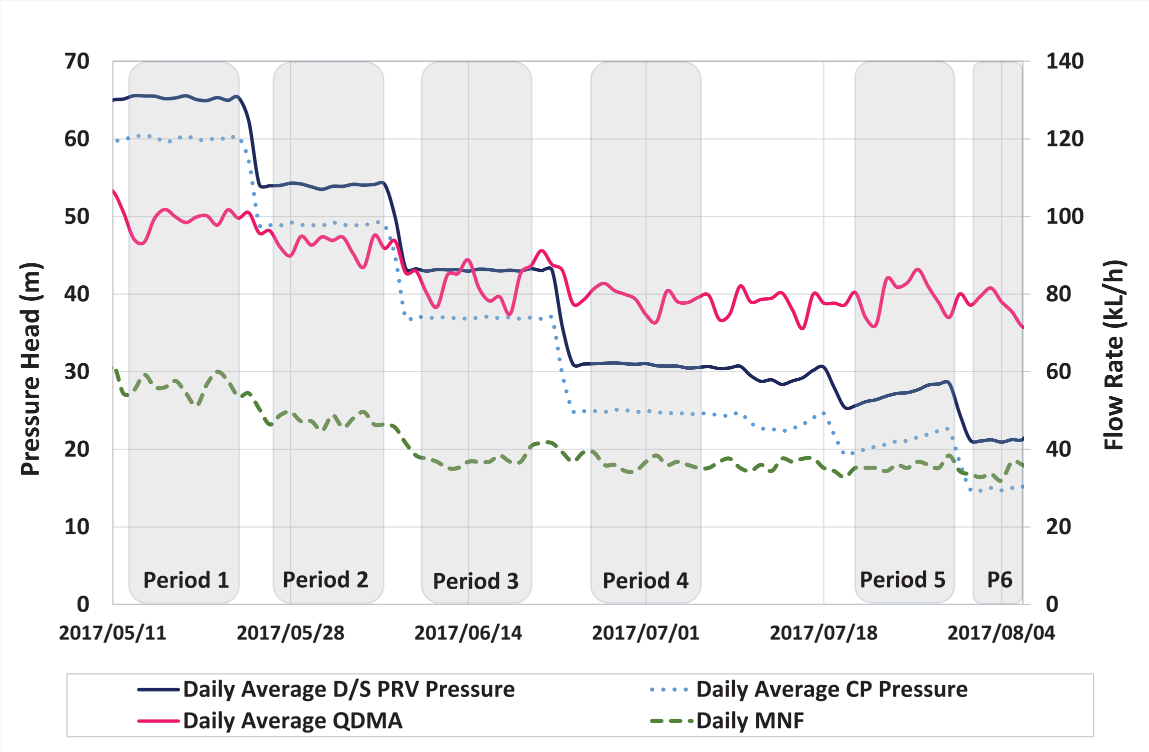

Figure 10: DMA3 time series pressure and flow profile

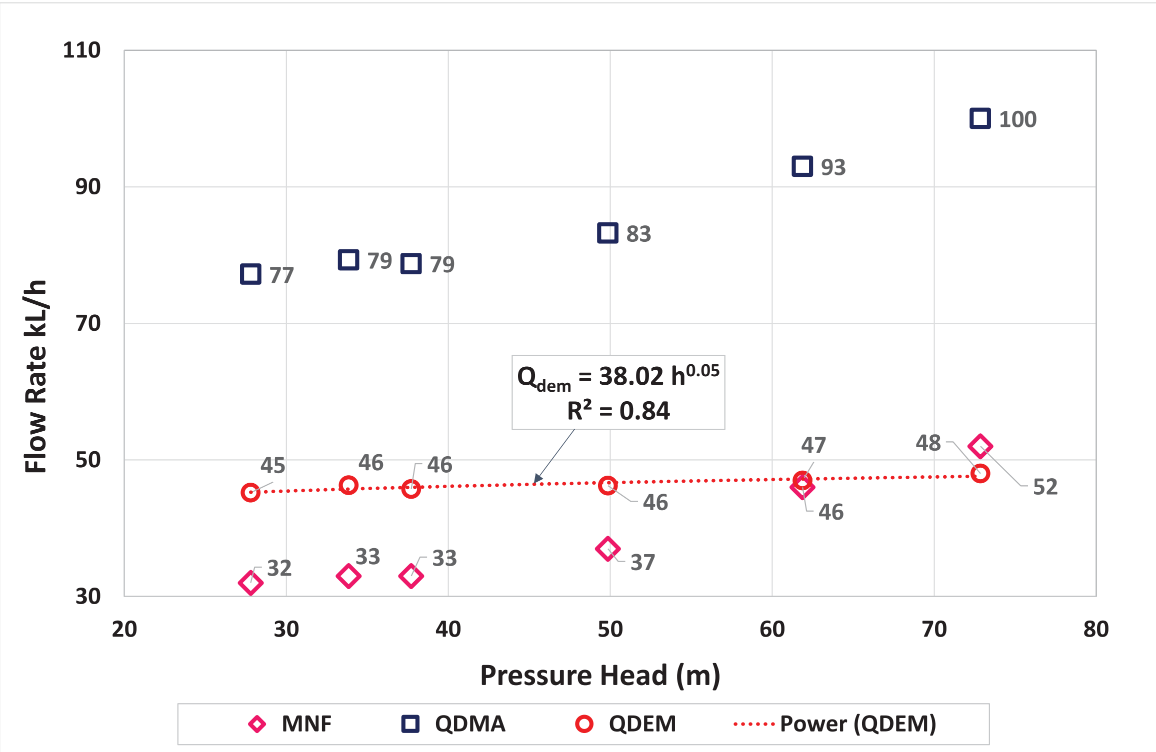

Figure 11: DMA3 Q_{DMA}, MNF and Q_{dem} versus pressure head

Figures 10 and 11 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. A trend line based on a power regression equation was fitted to the Q_{dem} values in Figure 8. The trend line indicate the approximate pressure-demand relationship for the particular case in question and do not take into account the potential role of other external factors on consumer demand.

4.3.2 DMA3 consumer flow data

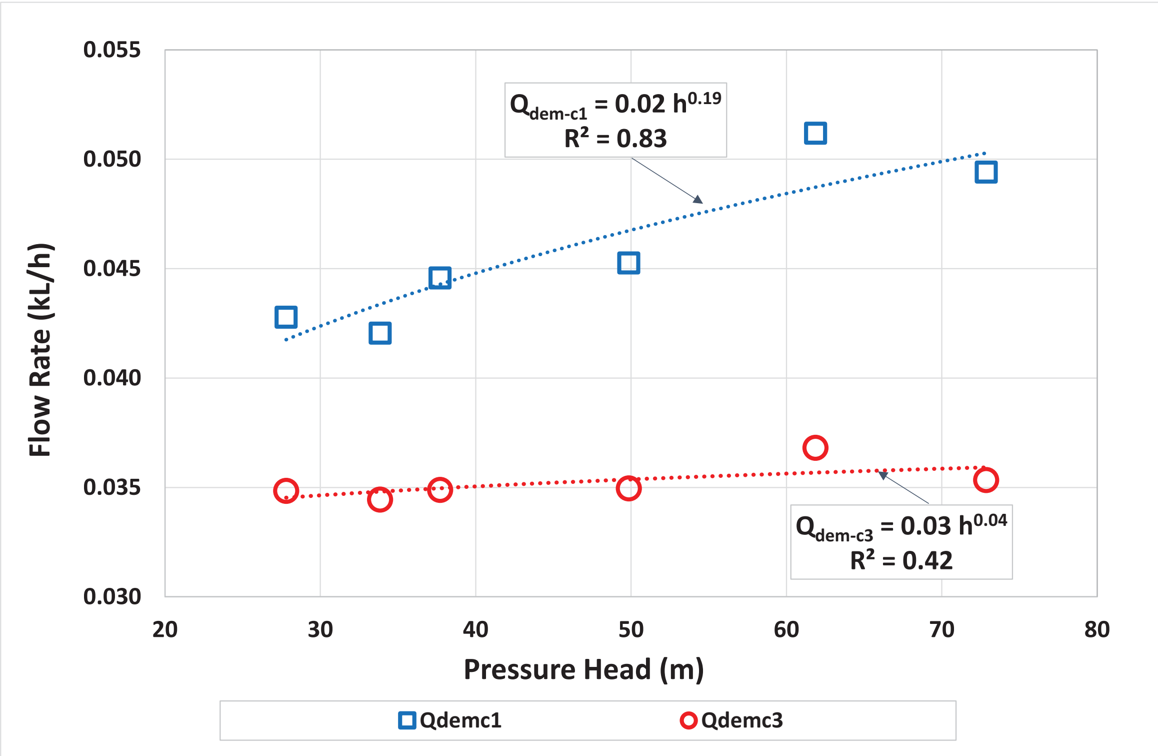

Figure 12: DMA3 $Q_{dem\ c1}$ and $Q_{dem\ c3}$ versus pressure head

Figure 12 show that $Q_{dem\ c1}$ and $Q_{dem\ c3}$ reduced with reduced pressure. Trend lines based on a power regression equation were fitted. The trend line for $Q_{dem\ c1}$ (all logged consumers) differed significantly from the trend line for $Q_{dem\ c3}$ (consumers with on-site leakage excluded) which suggest that on-site leakage plays a significant role in the pressure-demand relationship for DMA3.

5 ANALYSIS

5.1 Overview of Case Study Results

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. The elasticity of water demand to water pressure (β) refers to the sensitivity of demand to changes in pressure, and the elasticity values obtained in each case study are summarised in Table 11. As an example, an elasticity (β) of 0.25 would mean that the demand would decrease by 2.5% for every 10% reduction in pressure.

Table 11: Summary of elasticity of demand to pressure (β) from three case studies

	Elasticity of demand to pressure (β)		
	DMA Data	Individual Consumer Data	
	Q_{dem}	Q_{dem-c1}	Q_{dem-c3}
DMA1	0.07	0.13	0.26
DMA2	0.22	0.29	0.25
DMA3	0.05	0.19	0.04

Q_{dem} = Total consumer demand component for DMA which excludes leakage on the water distribution system and leakages at properties. This parameter was determined using recorded flow data at the DMA inlet meter. This parameter was analysed to establish i) if the flow data at the DMA inlet meter can be used to determine the pressure-demand relationship for the DMA as a whole and ii) to test if the Q_{dem} β values are similar to the Q_{dem-c3} β values for individual consumers without on-site leakage.

Q_{dem-c1} = Average demand for all individual consumers. This parameter was determined using the recorded data at the all the individual logged consumers. This parameter was analysed to determine the general pressure-demand relationship for consumers in each area.

Q_{dem-c3} = Average demand for individual consumers, excluding consumers where medium or high MNF was recorded. This parameter was determined using the recorded data at individual logged consumers where no MNF was visible. This parameter was analysed to determine i) the impact of on-site leakage on the pressure-demand relationship and ii) to test if the Q_{dem-c3} β values for individual consumers without on-site leakage are similar to the Q_{dem} β values for the DMA as a whole.

5.2 Comparison of elasticity of demand to pressure values

The elasticity of demand to pressure for the DMA as a whole (Q_{dem} β values in Table 11) represent the pressure-demand relationship for the DMA when all leakage in the DMA is excluded (in the water network and on-site at consumers). It was expected that Q_{dem} β for the DMA as a whole would be similar to Q_{dem-c3} β values for individual consumers in Table 11 where all consumers with potential leakage have been excluded from the calculation. The elasticity of demand to pressure (β) for each scenario is discussed below.

DMA1	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. 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.
DMA2	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}). Parameter Q_{dem-c1} β (0.29) did not differ significant from 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-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. The impact of household plumbing PRVs on the pressure-demand relationship in DMA2 is described in Section 5.6.
DMA3	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.

5.3 Elasticity of demand to pressure results from other studies

Study	Elasticity of demand to pressure (β)
Bartlett (2004) reported on the elasticity of demand to pressure (β) at a student village in Johannesburg.	0.2
Bamezai & Lessick (2003) in USA did not report on β values. The result obtained by them for general residential properties was equivalent to a β of 0.11.	0.11
Bamezai & Lessick (2003), the results obtained by them for properties where significant garden irrigation was expected was equivalent to a β of 0.24.	0.24
Moult (2018) analysed consumer billing data from Johannesburg to test the impact of pressure reduction on monthly consumer demand. The demand for the same calendar month before and after the project was compared and analysed (e.g. May 2014 vs May 2015). High income residential area where garden irrigation is expected and where on-site leakage is expected to be low.	0.34
Moult (2018), low income residential area where garden irrigation is expected to be limited and where on-site leakage is expected.	0.11
Moult (2018), high income residential area where garden irrigation is expected and where on-site leakage is expected to be low.	0.28
Moult (2018), medium income residential area where garden irrigation is expected and where some on-site leakage is expected.	0.21
Flow and pressure logging data for 12 low income DMAs were used to calculate the demand component (Q_{dem}) as per Eq (2): Q_{dem} = (Average Q_{DMA} – MNF). Q_{dem} refers to the demand downstream of the consumer but excludes leakage at consumer level. Criteria for selecting DMAs: residential DMAs, DMAs discrete, before and after period within a month from each other in order to minimise the potential impact of changes in weather, pressure head loss in the DMA between the inlet and the CP had to be relatively low (less than 15 m head loss), no garden irrigation noticeable in DMAs.	≤ 0.1 (11 areas) ≈ 0.3 (1 area)

5.4 Factors impacting on the pressure-demand relationship

By using the results from the field tests and from other studies three factors were identified which could influence the impact of pressure changes on demand, these being:

1. the presence of garden irrigation,
2. on-site leakage,
3. presence of household plumbing pressure reducing devices.

5.4.1 Garden Irrigation

Garden irrigation is usually pressure dependent and therefore a reduction in pressure should lead to decreased garden irrigation, and thus reduced consumer demand. It is expected that the elasticity of demand to pressure would typically be higher for outdoor use than for indoor use.

Results from case studies

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. 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 not the highest in DMA1. Further analysis showed that the demand in DMA1 increased in the latter part of the test when the pressure was at its lowest. This anomaly could be due to an increase in irrigation in the latter part of the dry season and this would have impacted on the calculated results. For this reason the Q_{dem} β for DMA1 should be viewed with caution.

DMA1 (High-Medium Income)	High garden irrigation is expected. β is not reliable for reason mentioned above.
DMA2 (Low Income)	Minimum visible garden irrigation. β of 0.29 which is higher than expected and could be related to the fact that fewer properties in this DMA had household plumbing PRVs (Refer to Section 5.6).
DMA3 (Medium Income)	Moderate garden irrigation. β of 0.19.

Results from other studies

Bamezai & Lessick (2003):	General domestic properties: β of 0.11
	Properties with garden irrigation: β of 0.24
Moult (2018)	Low garden irrigation areas: β of 0.11
	Moderate garden irrigation Areas: β of 0.21
	Higher garden irrigation Areas: β of 0.28-0.34

The results show that, even though there are some anomalies, a higher elasticity of demand to pressure can be expected for areas with higher garden irrigation (i.e. the demand should be impacted more through pressure reduction when there is significant garden irrigation compared to when there is no garden irrigation).

5.4.2 On-site leakages

Leakage is pressure dependent and therefore a reduction in pressure should lead to decreased consumer demand if on-site leakages are present.

DMA1 (High-Medium Income)	β = not reliable.
DMA2 (Low Income)	β of 0.29 where properties with on-site leakage were included.
	β of 0.25 where properties with on-site leakage were excluded.
DMA3 (Medium Income)	β of 0.19 where properties with on-site leakage were included.
	β of 0.04 where properties with on-site leakage were excluded.

The results show that a higher elasticity of demand to pressure can be expected for areas with higher on-site leakage (i.e. the demand should be impacted more through pressure reduction when there is significant on-site leakage compared to when there is no on-site leakage).

5.4.3 Household Plumbing PRVs

A potential factor that may influence the elasticity of demand to pressure 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 water network pressure are not expected to influence supply pressure at individual end-uses downstream of such a plumbing PRV, unless the water network 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 were not equipped with hot water geysers. This observation suggests that a large component of the indoor demand in DMA1 and DMA3 would not be affected by pressure changes in the water network if the supply pressure to properties remains above the household pressure control range. Since there are fewer properties with household plumbing PRVs in DMA2, a larger component of the demand is expected to be pressure dependent. This could partially explain why $Q_{dem}\,\beta$ was lower in DMA1 and DMA3 than in DMA2.

The results show that a higher elasticity of demand to pressure can be expected for some low income areas where properties do not have household plumbing PRVs (i.e. the demand should be impacted more through pressure reduction when there are no household plumbing PRVs compared to when each house is fitted with plumbing PRVs).

5.4.4 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. Where possible the comparative time periods for tests were selected to be within a month or two from each other or for the same month in two consecutive years to avoid the potential impact of weather changes on consumer demand.

6 MINIMUM PRESSURE REQUIREMENTS

6.1 International

Ghorbanian et al. (2016) summarised the minimum water pressure requirements for different countries (Table 12). 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 12: Minimum pressure standards (adapted from Ghorbanian et al., 2016)

	Minimum Pressure Standard (m)	
Region	**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	14	17.5
Michigan	-	24.5
UK and Wales	-	10
Brazil	-	15
Australia	20	-
New Zealand	10	-
Netherlands	-	20
Hong Kong	-	20

6.2 South Africa

In South Africa the *Regulations Relating to Compulsory National Standards and Measures to Conserve Water* (DWAF, 2001) stipulate that water networks 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. The actual achievable minimum pressure will differ from one area to the next and from one municipality to the next.

Under normal circumstances for the average residential area 24 m at the critical point should be sufficient. For low income areas with minimum garden irrigation and few water end-use points the minimum acceptable pressure may be lower than 24 m, and for some high income areas the minimum acceptable pressure may be higher as 24 m. Strijdom et al. (2017) noted that a theoretical minimum pressure of 10 m is required to ensure effective operation of some household appliances

During drought conditions municipalities may also consider lowering the minimum pressure requirements in order to achieve additional water savings. In 2018 the City of Cape Town experienced a drought and reduced the minimum pressure at critical points to 10-15 m for 4 hours in the morning, and 5-10 m for the remainder of the day (with the use of advanced pressure controllers).

7 IMPACT OF PRESSURE REDUCTION ON DMA INPUT VOLUME

The objective of this study was to test the pressure-demand relationship in a DMA (demand downstream of the consumer meter) which excludes the impact of pressure on leakage in the water reticulation network. Available information from other studies on the impact of pressure changes on the total DMA input volume is provided in this section as additional information.

7.1 Pressure-leakage relationship

The total DMA input volume will include leakage on the water network and therefore when the relationship between pressure and DMA input volume is considered the pressure-leakage relationship needs to be considered. The pressure-leakage relationship has been studied extensively and will not be covered in this study. A few of the prominent papers and publications on the pressure-leakage relationship include:

- Ledochowski (1956) presented one of the first papers on the pressure-leakage relationship. He used an equation to express leakage flow rate through an orifice.
- May (1994) proposed the well-known Fixed and Variable Area Discharges (FAVAD) equation, which is often referred to by water loss practitioners.
- 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. This equation is used in many of the pressure management analysis software programmes.
- Cassa et al. (2010) proposed an equation for modelling the effect of pressure on an individual leak which is similar to the FAVAD equation. May (1994) suggested that some leaks have fixed areas and others have variable areas, while Cassa et al. (2010) assumes that all leaks have certain areas that vary linearly with pressure, and that it is only the extent of the variations that differs.
- Van Zyl et al. (2017) highlighted that the generalised version of the FAVAD equation is an empirical equation and should only be used within its calibration pressure range. Van Zyl et al. (2017) recommended to use the modified orifice equation by Cassa et al. (2010) to describe the pressure-leakage relationship through leak openings.

7.2 Predicting the effect of pressure changes on DMA input volume

The potential effect of pressure changes on DMA input volume (savings) can be determined using existing methods, some of which are summarised below.

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7.2.1 Presmac Pressure Management Software

Presmac Software and user guide (WRC Report TT 152/01). The Presmac software was developed by the WRC and can be used to assess the theoretical potential water savings from implementing pressure management. PRESMAC uses the generalised version of the FAVAD equation for predicting the likely effect on leakage from changes in pressure. The Presmac software and user guide is available from the WRC website (www.wrc.org.za). Input requirements for Presmac include: pressure and flow logging data, length of mains, number of properties, elevations, etc.

7.2.2 Percentage MNF reduction method

Wegelin (2015) analysed the data for 23 new pressure management installations and showed a relationship between the percentage MNF reduction and pressure reduction. Equations were presented by Wegelin (2015) to estimate the potential savings (reduction in DMA input volume) from pressure reduction.

$$\text{\% Reduction in MNF} = 0.007 \times \text{Pressure Reduction (m)} + 0.187 \tag{3}$$

$$\text{DMA Inflow Reduction} = \text{MNF} \times \text{\% MNF Reduction} \times \text{Hour Day Factor} \tag{4}$$

It was stated that the Hour Day Factor normally varies from 28-22.

7.2.3 Pressure management case studies

The flow and pressure data for 28 residential DMAs from three metros were analysed and the reduction in DMA input volume for a 10% reduction in pressure was determined for each DMA. The DMAs were selected using the following criteria:

- DMAs had to be confirmed as discrete.
- PRV setting was lowered and the impact on DMA inlet flow was monitored.
- The before and after period had to be within a month or two from each other in order to minimise the potential impact of changes in weather.
- The pressure head loss in the DMA between the inlet and the CP had to be relatively low (less than 15 m head loss was considered acceptable).
- The difference between day and night pressure in the DMA had to be less than 20 m.

Table 13: Reduction in DMA Input volume for 10% Reduction in Pressure (28 DMAs)

Area Income	Garden Irrigation	MNF / AVG (%) *	Expected leakage	Reduction in DMA Inflow for 10% Reduction in pressure
Low	Low	≤40%	Low	1.9-2.6%
Low	Low	>40%	Medium	2.1-5.6%
Medium	Low to Moderate	≤40%	High	1.8-3.2%
Medium	Low to Moderate	>40%	Low	1.9-6.3%
High	Notable	≤40%	Medium	2.1-2.4%
High	Notable	>40%	High	2.3-6.4%

* The ratio of minimum night flow (MNF) to Average Flow (AVG) is a basic leakage indicator for a residential DMA. The higher this percentage the higher the expected leakage in the DMA.

8 SUMMARY

8.1 Pressure Demand Relationship (demand downstream of consumer meter)

The objective of this study was to test the pressure-demand relationship for residential DMAs (demand downstream of consumer meter). All research sites reported a positive relationship between pressure change and average consumer demand, where reduced pressure resulted in reduced average demand (demand downstream of the consumer meter). Based on the results presented in this study three significant factors were identified which could influence the elasticity of demand to pressure: 1) the presence of garden irrigation, 2) on-site leakage and 3) presence of household plumbing pressure reducing devices.

Garden Irrigation	A higher elasticity of demand to pressure can be expected for areas with higher garden irrigation (i.e. the demand should be impacted more through pressure reduction when there is significant garden irrigation compared to when there is no garden irrigation). The elasticity of demand to pressure was <0.10 for low irrigation areas, ≈0.10-0.20 for moderate irrigation areas and >0.2 for high irrigation areas. As an example, an elasticity (β) of 0.20 would mean that the demand would decrease by 2.0% for every 10% reduction in pressure.
On-Site Leakages	A higher elasticity of demand to pressure can be expected for areas with higher on-site leakage (i.e. the demand should be impacted more through pressure reduction when there is significant on-site leakage compared to when there is no on-site leakage). The elasticity of demand to pressure ranged from ≈0.15 to ≈0.30 where on-site leakage was included and ≈0.00 to ≈0.25 where on-site leakage was excluded.
Household Plumbing PRVs	A higher elasticity of demand to pressure can be expected for some low income areas where properties do not have household plumbing PRVs (i.e. the indoor demand should be impacted more through pressure reduction when there are no household plumbing PRVs compared to when each house is fitted with plumbing PRVs). This finding, suggests that indoor consumer demand (excluding on-site leakage) in some suburban areas may not reduce notably with 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.

The field exercise did however show that individual consumer demand would not always decrease with reduced pressure, and that in some cases the impact of non-technical aspects could surpass pressure-induced change for an individual consumer.

8.2 Impact of pressure reduction on DMA input volume

Results from other studies were included on the potential impact of pressure changes on the total DMA input volume. The total DMA input flow will be affected by the actual consumer demand and the leakage on the water network. Therefore, when the relationship between pressure and DMA input volume is considered the pressure-leakage relationship needs to be considered. Available methods / data were shown in Section 7 that can be used to estimate the potential reduction (savings) in the DMA input volume.

8.3 Minimum Pressure requirements

When pressure management is considered the minimum acceptable pressure for the area should be considered. The CSIR (2005) recommends a minimum pressure during peak demand of 24 m for residential areas in South Africa. The actual achievable minimum pressure will differ from one area to the next and from one municipality to the next. Under normal circumstances for the average residential area 24 m at the critical point should be sufficient. For low income areas with minimum garden irrigation and few water end-use points the minimum acceptable pressure may be lower than 24 m, and for some high income areas the minimum acceptable pressure may be higher as 24 m. Strijdom et al. (2017) noted that a theoretical minimum pressure of 10 m is required to ensure effective operation of some household appliances. During drought conditions some municipalities may also consider lowering the minimum pressure requirements in order to achieve additional water savings. In 2018 the City of Cape Town experienced a drought and reduced the minimum pressure at critical points to 10-15 m for 4 hours in the morning, and 5-10 m for the remainder of the day (with the use of advanced pressure controllers).

8.4 Conclusion

A basic planning guide presented in Annexure A can be used by municipalities to estimate the potential reduction in consumer demand and the potential reduction in DMA input volume from a pressure management initiative. A pressure management exercise should generally result in a reduction of the total input volume as well as a reduction in average consumer demand although the impact on consumer demand can in some cases be very low to negligible.

Factors to take into account in estimating the impact of a pressure management initiative:

- The higher the scope for pressure reduction the higher the expected impact on consumer water demand and input volume will be.
- In areas where the on-site leakage is high pressure management will have a larger effect on reducing consumer demand compared to areas with low on-site leakage (demand downstream of consumer meter).
- The consumer demand should be impacted more through pressure reduction when there is significant garden irrigation compared to when there is no garden irrigation (demand downstream of consumer meter).
- Higher savings should be achievable through pressure management in areas with high water network leakage compared to areas with low network leakage.

9 REFERENCES

Bamezai, A. & Lessick, D. (2003). Is system pressure reduction a valuable water conservation tool? Preliminary evidence from the Irvine Ranch Water district.

Bartlett, L. (2004). Pressure dependent demands in Student Town Phase 3: B.Eng. Final Year Project Report, Dept. of Civil and Urban Engineering, University of Johannesburg.

Cassa, A.M., Van Zyl, J. & Laubscher, R.F. (2010). A numerical investigation into the effect of pressure on holes and cracks in water supply pipes. Urban Water Journal, 7(2), 109-120, DOI: 10.1080/15730620903447613

CSIR (2005). Guidelines for Human Settlement Planning and Design. A report compiled by the CSIR Building and Construction Technology under the patronage of the Department of Housing.

Dibb, S., Simkin, L., Pride, W.M. & Ferrel, O.C. (2001). Marketing Concepts and Strategies, Fourth European edition. Houghton Mifflin, Boston

Gebhardt, D.S. (1975). The effects of pressure on domestic water supply including observations on the effect of limited garden-watering restrictions during a period of high demand. Water SA, 1(1), 3-8.

Ghorbanian, V., Karney, B. & Guo, Y. (2016). Intrinsic relationship between energy consumption, pressure and leakage in water distribution systems. Urban Water Journal 14 (5):515-521 http://dx.doi.org/10.1080/1573062X.2016.1223325

Girard, M. & Stewart, R. (2007). Implementation of pressure and leakage management strategies on the Gold Coast, Australia: Case Study. Journal of Water Resources Planning and Management. 133(3), 210-217 https://doi.org/10.1061/(ASCE)0733-9496(2007)133:3(210).

Gomes, R., Sá Marques, A. & Sousa, J. (2011). Estimation of the benefits yielded by pressure management in water distribution systems. Urban Water Journal, 8(2), 65-77.

Lambert, A. (2002). International report: water losses management and techniques. Water Science and Technology: Water Supply, 2(4), 1-20.

Lambert, A. & Thornton, J. (2012). Pressure: Bursts relationships: Influence of Pipe Materials, Validation of Scheme Results and Implications of Extended Asset Life. Proceedings of the IWA Water Loss Conference, 2012, Manila, Philippines.

Ledochowski, W. (1956). An analytic method of locating leaks in pressure pipe-lines. Transactions of the South African Institution of Civil Engineers, 6 (12): 341-344.

Martínez-Codina, Á., Cueto-Felgueroso, L., Castillo, M. & Garrote, L. (2015). Use of pressure management to reduce the probability of pipe breaks: A Bayesian approach. Journal of Water Resources Planning and Management, 141(9), 04015010:1-12

May, J. (1994). Pressure dependent leakage. World Water Environ. Eng. Manage. 17 (8) 13.

McKenzie, R. (2001). Presmac User Guide, South Africa Water Research Commission, WRC Report TT 152/01.

McKenzie, R.S. (1999). Development of a standardised approach to evaluate burst and background losses in water distribution systems in South Africa. South Africa Water Research Commission. WRC Report TT 109/99, ISBN 186845 490 8.

McKenzie, R.S., Mostert, H. & De Jager, T. (2004). Leakage reduction through pressure management in Khayelitsha: Two years down the line. Water SA, 30(5), 13-17.

Mckenzie, R.S. & Wegelin, W. (2005) Sebokeng/Evaton Pressure Leakage Reduction: Public Private Partnership. Proceedings from the IWA Specialist Water Conference: Leakage (382-391).

Meyer, N., Jacobs, H., Westman, T. & McKenzie, R. (2018). The effect of controlled pressure adjustment in an urban water distribution system on household demand, Journal of Water Supply: Research and Technology – AQUA.

Meyer, N. & Seago, C. (2017) Interpretation of logging results as a water network problem solving tool. South African Water Research Commission, WRC Report TT 737/17.

Moult, N. (2018). Assessment of consumer billing data for Johannesburg.

SANS 10252-1 2012. Water supply and drainage for buildings Part 1: Water supply installations for buildings, ISBN 978-0-626-26988-3

Strijdom, L., Speight, V. & Jacobs, H.E. (2017). Theoretical evaluation of sub-standard water network pressures, Journal of Water, Sanitation and Hygiene for Development, accepted for publication on 28 July 2017.

Thornton, J. & Lambert, A. (2005). Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships. Proceedings of IWA Special Conference on Leakage (12-14).

Van Zyl, J.E. & Clayton, C.R.I. (2007). The effect of pressure on leakage in water distribution systems. Proceedings of the Institution of Civil Engineers-Water Management. 160 (2), 109-114, Thomas Telford Ltd.

Van Zyl, J.E., Lambert, A. & Collins, R. (2017). Realistic Modeling of Leakage and Intrusion Flows through Leak Openings in Pipes. Journal of Hydraulic Engineering, 143(9), 04017030.

Weber, H. (2017). Telephonic Conversation, Kwikot geysers South Africa, October 2017.

Wegelin, W.A. (2015). Guideline for a robust assessment of the potential savings from water conservation and water demand management, Dissertation, Stellenbosch University.

Wegelin, W. and McKenzie, R. (2002). Leakage Reduction through Pressure Management: Concepts and Case Studies. South Africa Water Research Commission, WRC Report TT 186/02.

Willis, R., Stewart, R.A., Panuwatwanich, K., Capati, B. & Giurco, D. (2009). Gold Coast domestic water end use study. Water: Journal of the Australian Water Association, 36(6), 79-85.

10 ANNEXURE A – PLANNING GUIDE

A basic planning guide was prepared from the results obtained in this study that can used by municipalities to estimate the approximate impact of a pressure management initiative. It should be noted that the guideline presented below will not necessarily be accurate for every area and certain additional factors may impact on the results. These additional factors can include but not be limited to: changes in weather, changes in water tariffs, large fluctuation in pressure in a DMA, intermittent supply in parts or all of the DMA, unusual pressure-leakage relationship or unusual pressure-demand relationship for a specific DMA. When a more accurate assessment of the potential savings from pressure management is required it is advised to obtain flow and pressure logging data for the DMA and to analyse the data with one of the software packages available. It should also be noted that the guideline below was prepared with available data from a limited number of sites and as more data becomes available in future it may be possible to improve the guideline.

10.1 Step 1 – Assess potential for pressure reduction

The scope for pressure reduction in each DMA should be assessed. The minimum acceptable pressure in each DMA should be determined and this will vary from municipality to municipality and from one DMA to the next. Information on minimum pressure requirements are provided in Section 8.3. The existing pressure can either be measured with the use of pressure gauges / data recorders or the pressure can be estimated with the use of a hydraulic model. Once the existing pressures are known the scope to reduce pressure can be determined for each DMA.

For example, the average existing pressure at the critical point (CP) of a DMA is estimated to be 50 m and the minimum acceptable pressure for that DMA is 24 m. This suggest the pressure can be reduced by approximately 50% in this specific DMA.

10.2 Step 2 – Assess potential impact on demand and total DMA input volume

The reduction in residential consumer demand (demand downstream of consumer meter) can be estimated using the guideline below. It should be noted that the figures shown should only be used as a guide. The pressure-demand relationship will vary from one area to the next due to differences in consumer profiles, demand profiles and leakage levels inside houses.

Table 14: Reduction in Consumer Demand from Pressure Management

MNF / AVG	Expected On-Site Leakage Level	Garden Irrigation Level	% Reduction in residential consumer demand for 10% reduction in pressure	
			Min Factor	Max Factor
< 20%	Low	Low to Moderate	0%	1%
20% - 40%	Medium	Low to Moderate	1%	2%
> 40%	High	Low to Moderate	1%	3%
< 20%	Low	High	1%	2%
20% - 40%	Medium	High	2%	3%
> 40%	High	High	2%	4%

Notes:

1. Consumer demand mentioned above refers to actual consumer demand downstream of the consumer connection.
2. The MNF/AVG refers to the ratio of minimum night flow (MNF) over average logged flow. This ratio is used as one of the indicators of the leakage level in a system.
3. The figures shown above refer to residential consumers.

The reduction in input volume for a residential DMA can be estimated using the guideline below. Where a more accurate assessment of the potential savings from pressure management is required, it is recommended to obtain flow and pressure logging data for the DMA and to analyse the data with one of the software packages available.

Table 15: Reduction in Input Volume from Pressure Management

MNF / AVG	Expected Water Network Leakage Level	Garden Irrigation Level	% Reduction in DMA input volume for 10% reduction in pressure	
			Min Factor	Max Factor
< 20%	Low	Low to Moderate	1.5%	3%
20%-40%	Medium	Low to Moderate	2%	4%
> 40%	High	Low to Moderate	3%	6%
< 20%	Low	High	2%	4%
20%-40%	Medium	High	3%	5%
> 40%	High	High	3%	7%

Note:

The estimated reduction in input volume from pressure management includes the estimated reduction in consumer demand due to pressure management.

10.3 Worked Example

The annual input volume to a DMA was 500 000 kL/y and based on billing records the billed consumer demand to the DMA was 400 000 kL/y. If meter readings are not available the input volume and demand can also be estimated with the use of a hydraulic model. The leakage is expected to be high (MNF/AVG > 40%) and irrigation is expected to be low.

Step 1 – The average existing pressure at the critical point (CP) of a DMA is estimated to be 50 m and the minimum acceptable pressure for that DMA is 24 m. This suggest the pressure can be reduced by approximately 50%.

Step 2 – The expected reduction in demand and DMA input volume is shown below:

Approximate reduction in demand	Based on Table 14 (Row 3) the approximate reduction in demand will range from 1% to 3% for a 10% reduction in pressure, for this DMA. Based on 400 000 kl/y total demand the approximate reduction in demand is therefore expected to be in the range of 20 000kl/y to 60 000 kl/y, for a 50% reduction in pressure.
Approximate reduction in input volume for DMA	Based on Table 15 (Row 3) the approximate reduction in input volume will range from 3% to 6% for a 10% reduction in pressure, for this DMA. For 500 000 kl/y DMA input volume the approximate reduction in input volume is therefore expected to be in the range of 75 000 kl/y to 150 000 kl/y, for a 50% reduction in pressure. (The estimated reduction in input volume from pressure management includes the estimated reduction in consumer demand due to pressure management).