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

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ABSTRACT

The effect of pressure adjustments on individual consumer water demand is presented in this paper. The study involved collecting and analysing data from two sites in an operational water reticulation system in South Africa. Pressures and flow rates were monitored at a few strategic locations and at 44 individual homes during a series of controlled pressure adjustments. A total of 25 weeks' data, recorded at 15-minute intervals, were analysed. The two systems were subjected to 11 pressure adjustments, lasting 2 weeks each. Results showed a positive relationship between the average pressure change and median consumer demand, where reduced pressure led to reduced consumer demand. The linear model suggested a relationship of $\Delta Q \approx 0.5\Delta P$ between the change in average pressure and the change in median consumer demand, at a consumer connection. However, notable variation from one consumer to the next was apparent. Based on night flow analysis, the on-site leakage on consumer properties (downstream of the consumer meter) represented about 25% of the total metered demand of the study sample. The field tests also confirmed that there are practical limits to the level of pressure reduction that can be attained, beyond which the consumers become unsatisfied with the pressure.

Key words | leakage, pressure reduction, water demand

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INTRODUCTION

Reduction of water reticulation network pressure has been documented to be fundamental in water conservation and water demand management strategies (Gebhardt 1975; Bamezai & Lessick 2003; Girard & Stewart 2007). Reduced pressure has been linked to reduced infrastructure failures, reduced leakages and reduced water use. The focus in this study was on the effect of pressure change on actual individual household water demand, which excluded water reticulation network losses.

The impact of pressure reduction on consumer demand has been investigated in some previous studies. Bamezai & Lessick (2003) demonstrated that reduced water pressure can reduce residential demand, especially at properties where garden irrigation is common, while Cullen (2004) tested the pressure–discharge relationship for six types of irrigation devices and found that the discharge reduced with reduced pressure. Several South African case studies were reviewed by Wegelin (2015), noting that reduced system pressure resulted in reduced system input volume.

Reduced system pressure should, among other effects, result in reduced household demand. In order to address this shortcoming, full-scale trials were designed, focusing on the pressure–demand relationship of individual households. For the purposes of this research, 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.

The objective of the research was to determine the effect of controlled pressure adjustments on individual consumer

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demand in an operational water distribution system. The main advantages of recording and assessing individual household demand during pressure adjustment are: (i) the extent of on-site leakage on each consumer can be determined, which has a bearing on the individual consumer pressure–demand relationship, and (ii) the demand patterns of individual consumers can be analysed to determine how the effect of pressure on demand differs from one consumer to the next.

The methodology involved a knowledge review, followed by planning and implementation of field experiments with subsequent data analysis. Two district metered areas (DMAs) in two different residential areas were identified based on selection criteria, after which pressure and flow recording equipment was installed. The timing and pressure settings had to be scheduled, with consideration for minimum and maximum allowable pressures and possible consumer inconvenience during the experiments. Finally, the recorded data were analysed and results presented in order to draw a conclusion. A quantitative research method was selected to test the impact of controlled pressure adjustments on consumer water demand. The full-scale field experiments involved recording flow and pressure data while controlled pressure step changes were implemented.

SELECTION OF CASE STUDY SITES

DMA selection criteria

The data analysed in this study were collected through two full-scale field experiments, conducted in two DMAs which formed part of an operational water distribution system. The term 'DMA' was adopted from the UK water industry and 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). Both DMAs were located in the City of Tshwane (formerly Pretoria), the administrative capital of South Africa. The following criteria were used to select the DMAs:

- The DMAs had to be largely residential and supplied through a single water pipe connection fitted with a pressure reducing valve (PRV).
- The difference between the potential maximum and minimum PRV downstream pressure had to differ by 30 m or more to allow for notable pressure adjustments.
- The DMAs had to be confirmed as discrete with no open cross-boundary connections to adjacent areas.
- The pressure head loss along the distribution pipes 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. The CP is the node in a DMA where pressure is expected to be at a minimum.

Two DMAs meeting the above criteria were identified and are summarised in Table 1.

Verification of DMA discreteness

It was important to confirm, prior to the field experiments, that DMA1 and DMA2 were discrete. Any open cross-boundary connection would have impacted on the planned controlled pressure adjustments. In this regard, a number of checks were performed, which involved testing the pressures inside and outside the DMA boundaries and confirming that the pressures inside the DMAs did not correspond to the pressures outside the DMAs. As a further check a pressure drop test was undertaken in DMA2 and during this test the pressures inside the DMA dropped to near zero, while the pressures outside the DMA remained unchanged. These checks confirmed that both DMA1 and DMA2 were

Table 1 | Characteristics of selected DMAs

Description	DMA1	DMA2
Average income of consumers	Medium to high	Low
Total properties	1,201	4,683
Occupied properties	1,087	4,558
Residential properties according to municipal zoning code (expressed as a number and as a percentage of the occupied properties)	1,025 (94%)	4,547 (98%)
Total length of water pipes in DMA (km)	±24	±45
PRV elevation (m a.s.l.)	1,460	1,275
CP elevation (m a.s.l.)	1,462	1,280
Lowest geographical point elevation (m a.s.l.)	1,424	1,218

discrete, and thus suitable for pressure adjustment and further research. The DMA boundaries were also kept closed during the field experiments.

DATA COLLECTION

Data recording

Flow recording was undertaken by connecting data recorders to existing consumer water meters, and pressure recording was undertaken by connecting data recorders with a built-in pressure transducer to suitable access points (PRV or pressure connection). Locating and securing the equipment out of sight was critical in the light of infrastructure vandalism and theft problems prevalent in South Africa (Zindoga *et al.* 2010). Furthermore, the water meters concerned required a pulse output facility to connect to a data recorder, therefore, only certain types of water meters could be used. The Technolog Cello4 type data recorder was used to record pressure. A data recorder was placed at each PRV (inside the subsurface PRV chambers), and at each CP (inside custom built chambers with a pressure tapping on the mains). For consumer flow recording the Technolog Metrolog type data recorder was used. The data recorders at consumer meters were installed inside existing above-ground meter boxes and placed underneath the meters to decrease the possibility of theft. The volumetric recording sensitivity was 0.5 L per pulse. Flow data recorders were programmed for time-based recording using 15-minute intervals.

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 and 28 for DMA2, with one data recorder installed per consumer connection. Thus, the pressure and flow from 44 different homes in two DMAs were analysed as part of this study, with a total of 11 weeks' measurements in DMA1 and 14 weeks in DMA2. The consumers were selected to ensure a relatively even distribution between three ground elevation categories (near the CP, near the lowest geographical point, near the average geographical point) as well as between three daily water demand categories ($\leq$0.5 kL/d, $<$0.5 kL/d and $<$1.0 kL/d, $\geq$1.0 kL/d). Despite the relative significant data set, it was recognised that the consumer coverage was insufficient to extrapolate results to other regions beyond the study area. This study included data for 1.6% and 0.6% of all consumers in DMA1 and DMA2, respectively.

Non-technical variables, such as habits regarding water use, could not be controlled as part of this study and consumers were unaware of the research being conducted. During the installation of the data loggers, it appeared that none of the 16 selected consumers in DMA1 observed the data recorder installations, and in DMA2 it appeared that four of the 28 selected consumers observed the recorder installations. Consumers in the study sample were purposefully not informed about the field experiments and the research study in order to minimise consumer bias.

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 and maximum pressure at each consumer connection had to be prevented. The minimum pressure head criteria for house connections vary between 10 m and 25 m in different South African systems (Strijdom *et al.* in press), with a minimum value of 24 m pressure during peak hour demand reported in a widely used national guideline (CSIR 2005). Strijdom *et al.* (in press) noted that a minimum pressure of 10 m is required to ensure effective operation of some household appliances. For the controlled pressure adjustments a minimum system pressure head of 10 m was considered appropriate.

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, and each adjustment period was labelled (Period 1 to 5). The pressures at the CP had to be carefully monitored to avoid pressure violations. The minimum peak-hour pressure at the CP was 52 m in Period 1 (during the maximum pressure step) and ultimately reduced to 18 m in Period 5 (during the minimum pressure step). When the CP pressure reached 18 m, a number of low pressure complaints were reported via the municipality's normal consumer help-line. The PRV setting at −20 m was maintained for the 2-week period, but the intended further reduction to 10 m was not completed in DMA1. The field experiment was terminated after Period 5.

The field experiment in DMA2 was undertaken from 27 October 2016 to 31 January 2017. The PRV at DMA 2 was equipped with a GSM enabled electronic controller. 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, and each adjustment period was labelled (Period 1 to 6). The minimum peak-hour pressure at the CP was 40 m in Period 1 (maximum pressure step) and 10 m 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 related to blockages at consumer meters and the other two were noted to be unrelated to pressure by the municipal staff.

Data evaluation

The recorded pressures are shown in Figures 1 and 2, for DMA1 and DMA2, respectively. The small dots show the average daily pressure at the CP, which is slightly higher than the actual minimum pressure recorded during peak hour flow. The grey shaded areas in the figures represent the five data recording periods for DMA1 and six periods for DMA2. The water supply to DMA1 was unexpectedly interrupted (19–20 May 2016) and the water network was re-charged on 21 May. The data for the period 19–21 May, corresponding to the period of no-supply to this DMA and thus zero pressure and zero consumption by all consumers in the DMA over this period, were excluded from Figure 1 and the subsequent analysis. The supply-interruption was experienced at the end of the first 2-week analysis period (and before the start of the subsequent 2-week test period). Period 1 ended on 18 May before the water interruption and Period 2 commenced on 24 May after the system was re-charged. In this regard, the water interruption and

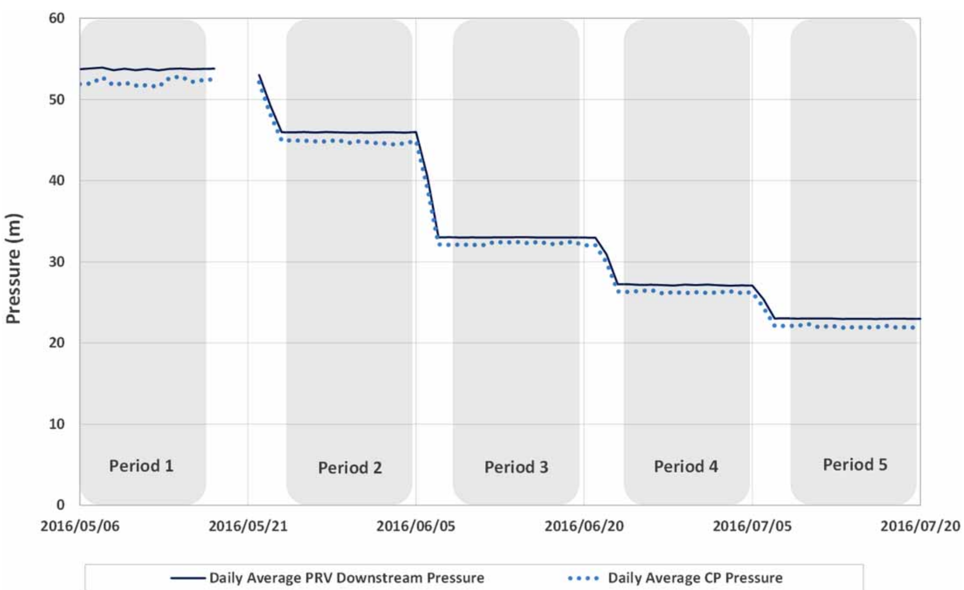

Figure 1 | DMA1 time series pressure profile.

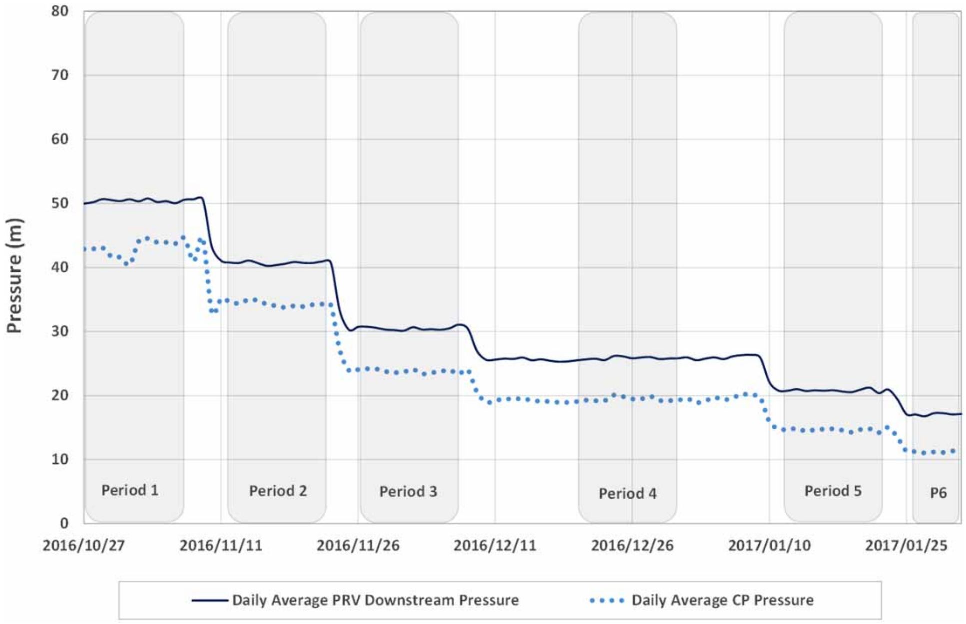

Figure 2 | DMA2 time series pressure profile.

exclusion of data were not considered to impact the results of the field experiment. Figures 1 and 2 show that the PRV downstream pressure and CP pressure reduced as intended, with each step.

The recorded water meter readings and pressure for each household were used to calculate the average water demand and average pressure for individual consumers during each recording period. Figures 3 and 4 were prepared by considering the change in average pressure for an individual consumer (during each recording period) versus the change in average water demand for the same consumer. The larger black circles in Figures 3 and 4 represent the

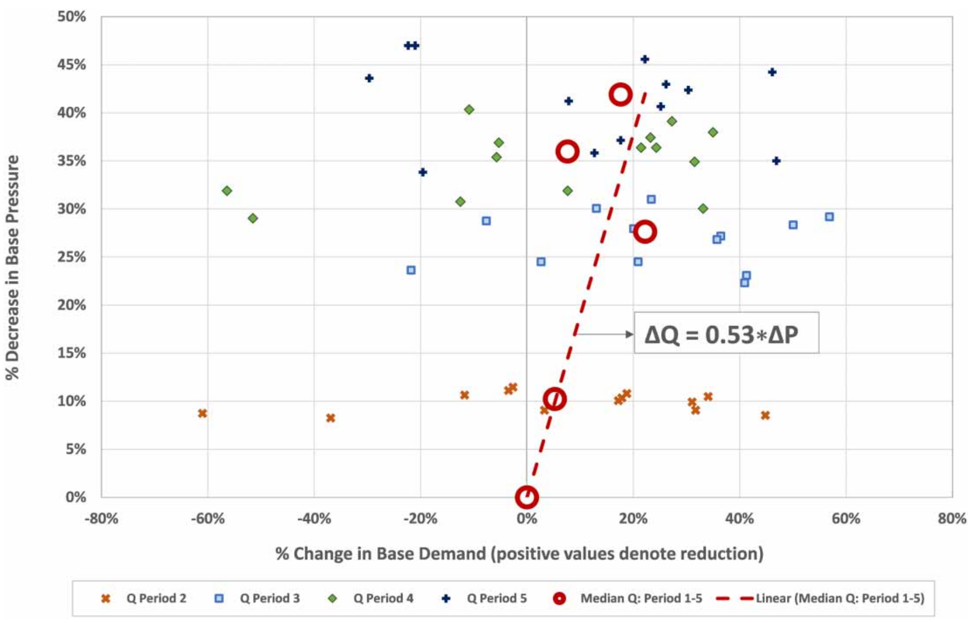

Figure 3 | Change in pressure versus change in consumer demand for DMA1.

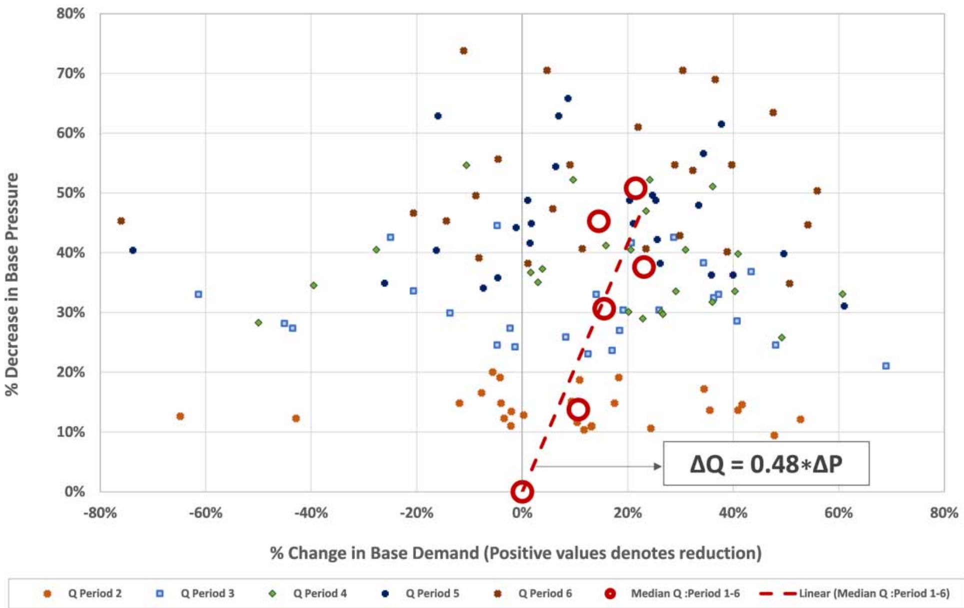

Figure 4 | Change in pressure versus change in consumer demand for DMA2.

median values for all consumers in each recording period. The data for one consumer in DMA1 and two in DMA2 were excluded from the analysis and are not shown in Figures 3 and 4, as discussed shortly.

The median values plotted in Figures 3 and 4 show reduced consumer demand (Q) with reduced pressure (P). A wide ΔQ-range is however apparent for individual consumers, with both figures including values recorded in the -80% to $+80\%$ range on the x-axis. All values for DMA2 were plotted in this range. In DMA1 the maximum ΔQ in the used data set was -176%, but it was considered appropriate to list the outliers instead of increasing the x-axis bounds to show those values. Only two consumers, both in DMA1, reported values outside the 80% bounds in the ΔQ-range. Consumer 1 reported three values outside the bounds (-124%, -86% and -137%) and for consumer 2 one value exceeded the axis-limits (-76%). Despite careful investigation, no grounds could be found to exclude these two consumers from the data set and both were included for further analysis.

An explanation of the data in Figures 3 and 4 is provided below:

- Individual consumer demand: Using the average individual consumer demand from Period 1 as the base, the percentage change in average individual consumer demand (ΔQ) was calculated for Period 2 to Period 5 in DMA1, and Period 2 to Period 6 in DMA2. The percentage value of ΔQ was plotted against the percentage change in pressure (ΔP) at the individual consumer, for each recording period. The pressure at each consumer was determined using the recorded pressure data from the CP and the ground elevations of the various consumers.
- Median consumer demand (median Q): Using the median consumer demand for all consumers from Period 1 as the base, the percentage change in median consumer demand (median ΔQ) was calculated for each period. The median ΔQ was plotted against the average ΔP at consumers. Linear trend lines were fitted to the median values and are discussed below.

DISCUSSION

Average pressure–demand relationship

The relationship between changes in median consumer demand and changes in pressure was generally positive for both samples of consumer data, where reduced pressure led to reduced demand. The relationship was, however, not consistent between various periods and, in some cases, the demand remained the same, or even increased slightly with pressure reduction.

Possible explanations for wide range in pressure–demand relationship for individual consumers

Stewart *et al.* (2009) reported notable variation in water consumption between individual households and between socio-economic regions. The relatively wide range in pressure–demand relationship for individual consumers can, in part, be attributed to the variance in household demand and the unpredictable demand patterns of people, which were 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. This highlighted that the impact of non-technical aspects on consumer demand should not be underestimated. Changes in the weather can also impact consumer water demand (Maidment & Miaou 1986; Gato *et al.* 2007), but weather-related parameters were not available for analysis during this study. In order to minimise the impact of weather, the case studies in DMA1 and DMA2 were undertaken over periods where the weather remained relatively constant. Another aspect to consider is that certain leaks and water usage components are influenced by pressure and are deemed pressure-dependent, while other leaks and water usage components are not influenced by pressure and are deemed pressure-independent (McKenzie 2001).

Linear relationship based on least squares fit

A linear trend line was fitted to the median values on Figures 3 and 4. The trend lines indicate the approximate linear pressure–demand relationship for the particular cases in question, even though it is acknowledged that the relationship varied significantly for individual consumers, as explained by the factors discussed above. The influence of the additional factors has not been evaluated in this study. The linear relationship (with intercept set at zero) between the Q and P for DMA1 is given by Equation (1), and the same relationship for DMA2 is given by Equation (2). The coefficients of determination (R^2) for Equations (1) and (2) were 0.40 and 0.76, respectively.

$$\Delta Q = 0.53\Delta P \quad (1)$$

$$\Delta Q = 0.48\Delta P \quad (2)$$

DMA1 is a medium-high income area, where garden irrigation is expected to be a notable contributor to the overall demand. Garden irrigation is pressure dependent and therefore a reduction in pressure should have led to decreased garden irrigation, and thus reduced consumer demand (Bamezai & Lessick 2003). It was expected that the impact of pressure on demand would be more significant in DMA1 than in DMA2, where garden irrigation is limited. The demand for a number of consumers in DMA1 increased in Periods 4 to 5, even though the pressure was reduced during this time. The higher demand was likely caused by increased consumer garden irrigation in the latter part of the dry season, driven by factors unrelated to the pressure change.

Logging data observations and exclusions

A significant minimum night flow (MNF) was recorded at a number of the consumers. The MNF evaluation and filtering was conducted subsequent to obtaining initial results (not presented in this paper), so that the impact on the results for each exclusion could be carefully considered. The data were analysed and results reworked after the MNF-filtering procedure.

The MNF is normally measured between midnight and 03h00, when most consumers will be asleep, and can therefore be used as an indicator of leakage. It is not unusual for properties to experience genuine night demand of around 2 L/h (Farley 2001) and, in some cases, the MNF could increase even more 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 paper the consumer MNF was defined as the steady minimum flow for a property over a period of 5 consecutive days or more. A summary of the consumer MNF is shown in Table 2.

Table 2 | Consumers per MNF category

	Consumers per MNF category (L/h)			
	None or low MNF ≤5	Medium 5 < MNF <15	High MNF ≥15	Total
DMA 1	8	5	3	16
DMA 2	20	5	3	28
Total	28	10	6	44

The flow data for the eight consumers with a high MNF (≥15 L/h) was scrutinised to decide whether these consumers had to be included or excluded in the 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:

- For three consumers (one in DMA1 and two in DMA2), the MNF increased consistently during the study period, and it was subsequently decided to exclude the data from the three consumers in the analysis. These exclusions did not significantly impact Equations (1) and (2), but did increase the respective R^2 values.
- Four consumers with a high MNF that were not filtered out experienced a high MNF for either 1 week or parts of 2 weeks, and this did not significantly impact the average flow over the duration of the field exercise. The last consumer with a high MNF that was not filtered out experienced a consistent MNF for most of the field exercise, but the MNF did not increase over time and the data from this consumer were included in the analysis.

The average consumer MNF was 7 L/h and 6 L/h in DMA1 and DMA2, respectively. The average MNF represented approximately 19% of the total demand of the consumers selected for flow recording in DMA1 and 32% in DMA2. The finding compares relatively well with the on-site leakage for a sample of properties in Johannesburg, where the average leakage was reported to be 25% of the household metered consumption (Lugoma *et al.* 2012). 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).

FUTURE RESEARCH

In order to improve the findings of this work a future project could set out to exclude on-site leaks at all properties in the study sample. An attempt could be made to identify sample homes without on-site leakage, or on-site leakage should be repaired prior to the pressure step-tests. The disadvantage would be that consumers would become aware of the ensuing research project, and thus results could include unwanted consumer bias.

CONCLUSION

A series of pressure adjustments in an operational water distribution system were successfully conducted to assess the impact of pressure change on 44 consumers' demand, in two separate study sites. Both research sites reported a positive relationship between the pressure change and consumer demand, with the linear model suggesting a relationship of $\Delta Q \approx 0.5\Delta P$ between the change in average pressure and the change in median consumer demand, at a consumer connection. Notable variation from one consumer to the next was, however, apparent. The relationship of $\Delta Q \approx 0.5\Delta P$ means, for example, that if the water network pressure is reduced by 10% the median consumer demand (which includes a component of on-site leakage) is expected to reduce by approximately 5%. The field exercise also confirmed that individual consumer demand would not necessarily reduce with reduced pressure and the impact of non-technical aspects on consumer demand should not be underestimated. Although this research did not focus on real losses in the distribution system, the on-site leakage on consumer properties (downstream of the consumer meter) were included in the analysis and represented approximately 25% of the metered demand of the consumers investigated. The field tests also confirmed that there are practical limits to the level of pressure reduction that can be attained, beyond which the consumers become unsatisfied with the pressure.

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