Research Paper

An assessment of sub-standard water pressure in South African potable distribution systems

Louis Strijdom, Vanessa Speight and Heinz Erasmus Jacobs

ABSTRACT

Sub-standard residual water pressures in urban water distribution systems (WDS) are a prevalent phenomenon in developing countries – South Africa being no exception. The phenomenon of sub-standard pressure is poorly understood, with intermittent supply ultimately resulting when there is no residual pressure left in the system. This research addressed the prevalence and extent of sub-standard pressures by using hydraulic models of potable WDS for 71 South African towns, located in 17 different South African municipalities geographically spread over the country. The hydraulic models included 539,388 modelled nodes, which were analysed to determine the number of nodes with sub-standard pressure heads during peak hour flow conditions. The results show that the residual pressure head was <24 m at 16.5% of the model nodes under peak hour flow conditions, with 6.7% of the nodes having pressure heads <12 m. In contrast, the results also report relatively high pressures in certain parts of the systems, far in excess of the minimum requirement, underlining the need for better pressure management at both high and low ranges. It was also noted that the South African design criterion is relatively stringent compared with some other countries and could potentially be relaxed in future.

Key words | distribution system, hydraulic model, water pressure

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INTRODUCTION

Background

In South Africa, there is a gap in coverage of providing basic water services to poor and disadvantaged communities which is exacerbated by rampant urbanisation, as is also the case in other developing countries. Over time, water networks have been expanded with the incorporation of previously unserviced consumers as well as new consumers, often without upgrading the main supply pipes. Peak flow rates increase over time and residual pressures decrease, often to sub-standard pressures.

One of the factors that drives the cost of potable water provision is the criteria used for design and hydraulic analysis of the water distribution system (WDS). A well known criterion for steady state analyses is the residual pressure head. The use of steady state demand-driven analysis with minimum pressure head (MPH) under peak hour demand remains a common criterion for system design (Jacobs & Strijdom 2009), despite the availability of more advanced reliability-based methods and head-dependent methods for distribution system analysis.

Minimum and maximum pressure heads can be obtained from steady state hydraulic model simulation results and are quantifiable, making them an obvious choice as performance indicators for water providing authorities. The MPH during peak flow is used worldwide as a criterion for system design. Most service providers also stipulate maximum

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allowable system pressure head, because unnecessary, high water pressures may result in water loss and leakage problems, as well as relatively higher water use. However, the focus in this research was on the MPH.

Rationale

There is a lack of data that clearly characterises the MPH during peak flow in water systems in South Africa, including the extent and scope of sub-standard pressures. The hypothesis that a notable portion of South African WDS do not meet the criteria of 24 m MPH was investigated in this study. Hydraulic network models for numerous South African towns were obtained in addition to the relevant actual monthly water use for each individual consumer over a period of 1 year. Monthly water meter readings were analysed to derive peak hour flow rates, subsequently used to populate the hydraulic models. The outcome of this study identifies the scope of the problem and provides an evidence base for considering whether changes to the design criteria for MPH in South Africa would be beneficial. Furthermore, this study highlights some of the causes of sub-standard system pressure to assist with mitigation of those problems in the future.

Review of minimum pressure standards

In England and Wales, pressure is under the jurisdiction of the economic regulator, Ofwat, as part of the guaranteed service scheme. This regulation requires that water companies maintain a minimum of 7 m of pressure head at the point of connection to the customer's premises (Ofwat 2008). Under this scheme, if the pressure falls below this level on two occasions, with each occasion lasting at least one hour, during a 28-day period, then the customer is entitled to financial compensation. In practice, most water companies have internal standards ranging from 10 m to 20 m for their water pipes to ensure that the customer standards are met. The Water Industry Act (UK Parliament 1991) further requires that water be supplied constantly and at such a pressure as will cause the water to reach to the top of the topmost storey of every building within the distribution system. Ofwat also uses a performance indicator regarding MPH called 'Properties at risk of low pressure' to evaluate system performance. Performance is measured by testing that 10 m head of pressure is provided at the customer's external stop tap at a flow of nine litres per minute, which should be sufficient to fill a one-gallon container in thirty seconds (Ofwat 2016). Compliance with this pressure performance measure does not override the utilities' duty to comply with the Water Industry Act standard for pressure at the topmost storey.

In the USA, design criteria guidance manuals recommend that the minimum pressure should be 14.1 m (20 psi) at all times, even during a fire event superimposed on peak demand conditions (AWWA 2008, 2012; GLUMRB 2012). Furthermore, the US Environmental Protection Agency lists maintenance of positive pressure in all parts of the distribution system as a best practice to avoid microbial contamination (USEPA 2016a) and several states have interpreted this regulation to require that a boil water notice be issued to the public within 24 hours if the pressure drops below 14.1 m (USEPA 2016b). AWWA (2012) recommends that the range of operating pressures be between 21.2 m (35 psi) and 63.2 m (90 psi) under typical operating conditions, including peak demands. Many water utilities have used these design criteria and recommendations to develop internal MPH targets of 21.2 m (35 psi) to 28.1 m (40 psi) that are used in analysing system performance and sizing new distribution system components (WSSC 2008). Similarly, in Canada, the provincial design guidance manuals reference the AWWA (2008) and GLUMRB (2012) documents and require a minimum pressure of 14.1 m (20 psi) under maximum demands plus fire flow with a minimum pressure of 28.1 m (40 psi) under normal operating conditions (MOE 2008).

Colombian legislation ranks cities and towns according to population and economic capacity of the citizens in classified groups called 'system complexity levels'. For each of these levels the MPH differs with the minimum being 10 m head for areas with less than 2,500 inhabitants; for large cities the MPH should exceed 20 m in residential areas and 25 m for non-domestic use (Saldarriaga *et al.* 2008).

Two WDS types are considered in Australian design criteria, namely potable WDS and recycled WDS. The minimum and maximum pressure criterion were the same for both system types at the time of publication, but may not necessarily remain the same in future. The Australian water-governing body provides minimum pressure requirements of 22 m (WSAA 2007). The City of Gold Coast, the local government area spanning the Gold Coast, Queensland and surrounding areas in Australia have several statutory water authorities that are governed independently, with the desired minimum service pressures under normal operating conditions varying slightly across the region from 21 m to 22 m (City of Gold Coast 2012; Queensland Competition Authority 2014).

The World Bank has indicated that about 13% of urban water users in China receive water at inadequate pressure (Browder 2007). However, no reference was made to what pressure value was deemed 'inadequate'. For Vietnam, the national design standards indicate a MPH of 10 m (Government of Vietnam 2006).

A MPH of ≥24 m has long since been the norm in South Africa. In the first South African publication of this nature Leslie (1957) suggested an 'absolute minimum' of 12 m for low-income and 15 m for high-income areas. The criterion currently in use was published as a guideline for the provision of engineering services by the South African Council for Scientific and Industrial Research (Crabtree & Cameron 1983; CSIR 1983), with the latest revision unchanged in terms of the pressure criteria (CSIR 2005). The guideline stipulates that the MPH for the most critical node in a WDS during peak flow should exceed 24 m at the consumer connection. However, most of the large metropolitan municipalities in South Africa have switched to in-house criteria, because the 24 m has become outdated and was never published as a national standard. The minimum supply pressure required for certain domestic appliances to operate adequately was published as a national standard (SANS 2012), but the standard does not relate to pressure at the consumer connection to the distribution system. Among the sanitary fixtures and fittings the most critical item is a toilet with automatic shut-off flush valve (also called 'pressure flush toilet') with an MPH requirement of 20 m, but pressure flush toilets are uncommon in South Africa. Jacobs & Strijdom (2009) noted that some appliances such as the dishwasher and washing machine require a MPH of ~10 m to operate.

The MPH requirements for the different countries are summarised in Table 1, with a focus on the pressure during maximum hourly demand. The minimum pressure during

Table 1 | Summary of selected international MPH requirements

Country, Region, City	Source	MPH (m)
South Africa (Countrywide)	Leslie (1957) CSIR (1983) CSIR (2005)	12–15 12–24 10–24
South Africa (City of Tshwane)	City of Tshwane (2010)	16–24
South Africa (Ekurhuleni)	EMM (2007) and EMM (2011)	15–25
USA	AWWA (2008) AWWA (2012) GLUMRB (2012)	14[a] 21 21
New Zealand	Ghorbanian *et al.* (2016)	25
Canada (Ontario)	MOE (2008)	28
Canada (British Columbia)	Ghorbanian *et al.* (2016)	28
Canada (Alberta; Saskatchewan)	Ghorbanian *et al.* (2016)	35
Australia (Countrywide)	WSAA (2007)	22
Australia, Gold Coast	City of Gold Coast (2012) and QCA (2014)	21–22
United Kingdom (England and Wales)	Ofwat (2008) Ofwat (2016) UK Parliament (1991)	7 10[b] Sufficient for pressure on topmost storey of all buildings
Columbia (Countrywide)	Saldarriaga *et al.* (2008)	10–30
Vietnam (Countrywide)	Government of Vietnam (2006)	10

[a] Under maximum demand conditions plus fire flow.

[b] Performance measure, not a requirement.

peak hourly demand is widely used when considering minimum system pressure (Ghorbanian *et al.* 2016), although the 15-minute peak has been reported to approximate actual maximum peak flow (Johnson 1999). Events with much shorter durations have also been investigated. For example, Ghorbanian *et al.* (2016) determined whether transient pressures violate pressure standards. In this paper, the term substandard applies to South African conditions, where the peak hour demand is used as representative of the peak flow.

APPROACH

A quantitative theoretical approach was used to assess the MPH during peak flow in this study, based on an analysis of available hydraulic models for South African distribution systems. Actual system pressure and peak flow rates were not recorded as part of this research.

Limitation regarding fire flow

The South African design guidelines, discussed earlier (CSIR 2005), suggest that potable water supply systems should have the capacity to provide for firefighting in addition to normal peak flow. The required flow for firefighting typically exceeds the peak hour flow under normal circumstances; fire flows thus generally govern the design of WDS. However, in over-stressed systems that fail to meet MPH requirements during normal peak flow conditions – typical of those analysed as part of this research – limited value would be added by superimposing fire flows.

Some researchers have questioned the sensibility of providing fire flow via the potable distribution system in the first place. Snyder & Deb (2003) noted that the larger required infrastructure to meet fire flows would have a degrading effect on water quality due to the increase in water age in the system and proposed a number of firefighting alternatives. Furthermore, Myburgh & Jacobs (2014) found that only about 8% of all fires in their study sample were extinguished using potable water from the distribution system; the majority of fires were extinguished by means of water ejected from pre-filled tanker vehicles. Provision of tanker supply or compressed air foam for firefighting has been noted to be more cost effective for fire provision than increasing the size of the water processing facilities and distribution system (National Research Council Canada 1997; Davies 2000). The concept of water provision for firefighting from the distribution system could possibly change in the future with the implementation of firefighting alternatives. It was considered appropriate to exclude fire flows in this research study so as to focus on MPH under normal peak hour flow conditions, which should not be taken as an indication that fire flow requirements could be waived during system design.

Study sample – overview of hydraulic models analysed

Hydraulic models for all metropolitan municipalities in South Africa, excluding only Nelson Mandela Bay (Port Elizabeth) and eThekwini (Durban) were analysed. In order to obtain a representative sample for different types of settlements and consumers, the hydraulic models for several district municipalities and smaller local municipalities spread over South Africa were included in the study sample. The smaller municipalities were selected specifically to include inland and coastal regions as well as to cover the different climatic regions of South Africa. In total, 71 different towns located within 17 different municipal areas of jurisdiction were included in this study. Some adjacent towns (for example those with a shared water source) comprised a single hydraulic model. A total of 52 different hydraulic models comprising a total of 539,388 modelled nodes were ultimately analysed. The town names were not presented or linked to results, because the town names or locations were not essential in order to draw conclusions.

All the water system models used as part of this research were at the time used in parallel by professionally registered civil engineers at GLS Consulting (www.gls.co.za) to conduct water master planning for the systems in question. The hydraulic models used in this study were obtained directly from collaborators at GLS Consulting. All the received models were fully populated with water demand (node outputs), but the water demands for all the acquired hydraulic models were repopulated by the research team with the latest available data in order to remain consistent in terms of the peak hourly flow rate in all systems. The largest model analysed was the City of Cape Town, where hydraulic models of different suburbs were merged into a single model with ~126,000 nodes. The smallest model analysed was a coastal holiday town along the West Coast, with only 95 nodes and a single pressure zone.

Software application

A modified demand-driven analysis was conducted for the steady-state peak hour condition in all hydraulic models. For all hydraulic analyses performed in this study, the commercial software package WADISO 5 (www.gls.co.za) was used. WADISO uses the standard EPANET (Rossman 2000) engine to perform demand-driven hydraulic analysis. A standard demand-driven analysis first imposes the demands on the network and then analyses the resulting pressures, meaning that node outputs are known steady-state functions and are independent of system pressure. The relationship between pressure and demand is thus ignored (Cheung *et al.* 2005). Demand-driven analyses should be used with caution for systems with relatively low pressures, because the fixed demand could result in unrealistic negative pressures.

Analyses that incorporate the relationship between demand and pressure are referred to as pressure driven analyses. Wagner *et al.* (1988) proposed a simulation method to produce more realistic results whereby, 'Nodes are targeted to receive a given supply at a given head. If this head is not attainable, supply at the node is reduced.' An extension of the standard EPANET solver exists that directly includes pressure driven analysis, the data structures and algorithms within EPANET source code are modified in such a way that fixed demand is assumed above a given critical pressure, zero demand is induced below a given minimum pressure (typically near zero) and some proportional relationship between pressure and demand is provided for intermediate pressures (Cheung *et al.* 2005). The EPANET extension was not used directly in this research, but instead a similar procedure was applied in WADISO for zones where the demand-driven analysis resulted in near-zero or negative nodal pressures.

Demands

The actual monthly water use per individual consumer, as recorded via the consumer water meter (in kL/month), formed the basis of the peak flow calculation in the hydraulic models. The monthly water meter readings are used for billing consumers in South Africa, with consumers typically billed for water monthly, based on actual water use. Monthly water meter readings, used for billing, are recorded in the municipal financial billing systems, also called treasury systems. Jacobs & Fair (2012) described a software tool called SWIFT that was also used in this research to extract monthly metered water use from treasury systems while maintaining spatial integrity of the data, meaning that each water meter could be plotted on a map and could thus be linked to hydraulic model topology. SWIFT has been employed for numerous research studies in Southern Africa over the past two decades (Jacobs & Fair 2012).

Hydraulic models were populated with the hourly peak flow rate, which is derived from the average annual daily demand (AADD). The AADD is widely used for problems relating to research and design in South Africa, and is also used in other Southern African countries, for example, in Malawi (Makwiza & Jacobs 2016). The AADD is determined for each individual consumer by adding the monthly water use for the particular consumer over a year; in a SWIFT analysis this would imply the most recent 12 months prior to extraction of the water meter readings from the treasury system. The AADD is thus based on the actual monthly consumer water meter readings for the most recent 12 months prior to data extraction. The total annual water use for each consumer (in kL/year) is thus found, and then divided by 365. The measurement units are converted to L/s in order to calculate the AADD. Each consumer in the study area would thus have an AADD (L/s) based on the consumer's actual water use.

For the majority of the analysed municipal areas, SWIFT was used to calculate each consumer's AADD. For SWIFT to work, reliable monthly water meter readings need to be available in the treasury system, as used for billing by the municipality. For a few of the smaller municipalities, reliable treasury data was not available, so a manual process had to be performed to assign theoretical AADD values to consumers, based on available land-use and plot-size information. Each consumer was thus assigned a theoretical unit water demand (UWD). The UWD allocated to each of the different consumer types included in the study, is summarised in Table 2. In order to allocate the AADD to a consumer for which no water meter readings were available, the analyst would identify the land use code from the town planning records and then identify the corresponding type of consumer in Table 2 (in the column 'land use'). The UWD (kL/unit) value would then be used as the

Table 2 | Typical South African UWDs per consumer type

	Typical density[a] (Units/ha)		UWD		
Land use	**Range**	**Typical**	**(kL/ha)**	**(kL/unit)**	**Unit**
Rural homes	<3	1.0	3.0	3.00	Plot
Suburban home: Extra-large erven	3 to 5	4.0	10.0	2.40	Plot
Suburban home: Large sized erven	5 to 8	6.5	12.0	2.00	Plot
Suburban home: Medium sized erven	8 to 12	10.0	13.0	1.60	Plot
Suburban home: Small sized erven	12 to 20	14.0	15.0	1.20	Plot
Cluster homes: 20 to 30	20 to 30	25.0	20.0	1.00	Household unit
Cluster homes: 30 to 40	30 to 40	35.0	25.0	0.80	Household unit
Cluster homes: 40 to 60	40 to 60	50.0	30.0	0.70	Household unit
Flats	60 to 100	80.0	50.0	0.60	Household unit
Low cost housing homes	20 to 30	25.0	5.0	0.25	Household unit
Informal relocated homes	18 to 25	20.0	5.0	0.25	Household unit
Informal upgraded homes	18 to 25	20.0	15.0	0.75	Household unit
Informal upgraded low cost homes	18 to 25	20.0	5.0	0.25	Household unit
Low cost housing	15 to 20	20.0	13.0	0.60	Plot
Business/Commercial	N/A[b]	40.0	25.0	0.80	100 m² floor area
Industrial	N/A[b]	40.0	20.0	0.40	100 m² floor area
Warehousing	N/A[b]	40.0	20.0	0.60	100 m² floor area
Mixed land use	N/A[b]	40.0	25.0	0.80	100 m² floor area
Parks & sports fields	N/A[b]	1.0	15.0	15.00	Area (ha)
Densification (Res)	N/A[b]	25.0	20.0	1.00	Household unit
Densification (BCI)	N/A[b]	60.0	40.0	0.80	100 m² floor
Education	N/A[b]	40.0	15.0	20.00	Household unit
Institute	N/A[b]	40.0	15.0	20	100 m² floor area

[a] The typical density was not used in calculations. The UWD was determined for those consumers where metered use was unavailable. The typical density is added as a means of comparison to other regions.

[b] The density of these land uses varies notably and typical values were considered to be inappropriate.

consumer's AADD. This process would be repeated for each consumer (or group of similar consumers) for which actual values were not available from SWIFT.

Peak factors

Flow rates in a WDS vary throughout the day, resulting in peak flows during times of high usage. Various methods are available for determining the peak flows and representing these within hydraulic models. In South Africa, it is common practice to multiply the AADD with a corresponding peak hour factor in order to estimate the peak hour flow rate. In this research, the peak factors by Vorster *et al.* (1995) were employed, which is in line with the practice used by all municipalities reported on in this study; the peak hour factors are between 3.0 and 4.6 times the AADD.

The peak flow rate of each consumer was allocated to the model node nearest to the centre of the consumer's GIS-parcel, representing a property. As part of the procedure, a cross-reference was made between each individual customer's GIS-parcel and each node in the water model to geographically allocate the peak flow rate for each consumer to the nearest hydraulic model node with an automated GIS-tool, as explained by Jacobs & Fair (2012).

The AADDs of about 4.9 million individual consumer records, of which 3.5 million represented occupied homes, were determined as part of this project with SWIFT (the remaining 1.4 million records were either vacant plots or unoccupied homes with no water use). The calculated peak flows for each of the consumers were subsequently cross-referenced to the appropriate model node. The total peak flow rate was thus determined for each model node. The existing operational scenarios were used for each model to simulate the current status quo as closely as possible.

Statistical analysis

After performing the hydraulic analyses, the nodal result tables were exported to Microsoft Excel to perform further statistical analyses. The set of nodal results were statistically analysed for each model run to include the sample size (number of model nodes), the average MPH (average of the pressure head at nodes under peak hour flow conditions), the standard deviation of MPH and the percentage of nodes with MPH values within certain predefined pressure head categories. The pressure head categories are called H-categories in this paper.

RESULTS

The results, summarised in Table 3, show great variation in the average MPH for the models analysed. The average MPH in each system was used as an indication of the pressure in each network model. Average MPH for the models ranged from as low as 11.1 m to as high as 64.8 m. Four models had an average MPH below 24 m criterion for minimum pressure. While average MPH is not a good indicator for compliance with the MPH criterion, very low average MPH values could be indicative of models that would fail the MPH criterion when individual nodes are examined. However, one model had a relatively high average MPH of 41 m, while a third of the same model nodes experienced MPH values below the minimum criterion of 24 m. Most of the models analysed had an average MPH of between 36 m and 48 m.

The most significant results relate to the percentage of nodes with sub-standard pressure, thus MPH < 24 m. The percentage of nodes with MPH < 24 m were ranked and plotted in Figure 1. The criterion of MPH ≥ 24 m at the most critical node was only achieved in one model, meaning that only one distribution system could meet the pressure

Table 3 | Summary of 52 individual hydraulic model results for MPH

Model number and location (province)		Nodes in model	Average MPH (m)	St. Dev of MPH	% Nodes with $H < 24$ m
1	Eastern Cape	14,726	37.7	18.3	24.9
2	Eastern Cape	8,602	42.3	17.9	15.7
3	Eastern Cape	6,651	36.9	22.5	28.9
4	Free State	669	11.1	12.7	80.9
5	Gauteng	44,605	57.5	26.5	6.5
6	Gauteng	31,420	37.4	19.1	22.2
7	Gauteng	17,420	64.7	22.3	3.7
8	Gauteng	15,443	47.3	28.2	18.7
9	Gauteng	15,388	30.4	20.6	41.8
10	Gauteng	14,255	38.5	13.4	12.9
11	Gauteng	13,503	50.4	21.7	8.0
12	Gauteng	13,340	58.5	24.1	3.7
13	Gauteng	12,723	41.6	19.9	15.2
14	Gauteng	12,636	62.6	25.9	5.6
15	Gauteng	12,538	54.7	26.8	12.7
16	Gauteng	12,412	63.2	25.2	3.4
17	Gauteng	12,409	41.1	19.7	17.1
18	Gauteng	11,411	31.8	15.3	28.4
19	Gauteng	10,131	40.6	26.0	27.4
20	Gauteng	10,042	30.3	13.9	34.8
21	Gauteng	9,479	47.6	21.8	11.2
22	Gauteng	8,471	44.8	22.1	17.4
23	Gauteng	7,813	55.7	20.5	3.7
24	Gauteng	6,744	23.9	14.7	45.8
25	Gauteng	6,182	25.4	56.7	44.4
26	Gauteng	5,668	48.4	19.1	6.6
27	Gauteng	4,765	49.8	39.4	21.0
28	Gauteng	4,138	58.0	19.7	2.1
29	Gauteng	3,287	23.1	17.3	54.2
30	Gauteng	3,041	39.1	15.8	18.0
31	Gauteng	2,879	48.0	19.0	8.5
32	Gauteng	2,338	53.1	30.1	16.8
33	Gauteng	2,138	31.3	15.1	29.7
34	Gauteng	779	48.5	27.6	18.5
35	KwaZulu-Natal	7,617	38.3	21.8	31.1
36	KwaZulu-Natal	4,867	60.5	49.8	16.1
37	Mpumalanga	5,892	44.4	23.3	24.3
38	Northern Cape	1,184	19.3	11.7	60.3
39	Northern Cape	936	27.5	7.2	31.4

(*continued*)

Table 3 | continued

Model number and location (province)		Nodes in model	Average MPH (m)	St. Dev of MPH	% Nodes with H < 24 m
40	Western Cape	126,072	51.0	18.7	11.4
41	Western Cape	15,981	41.6	20.2	21.2
42	Western Cape	5,715	40.8	14.1	8.1
43	Western Cape	3,012	41.2	27.3	33.2
44	Western Cape	2,796	29.7	21.9	40.4
45	Western Cape	1,472	24.7	20.7	54.7
46	Western Cape	1,418	30.1	26.3	43.2
47	Western Cape	1,411	40.0	18.5	21.1
48	Western Cape	1,271	47.1	23.3	12.7
49	Western Cape	1,017	56.7	22.4	8.5
50	Western Cape	339	37.4	18.6	19.5
51	Western Cape	247	29.6	6.4	26.7
52	Western Cape	95	60.6	5.6	0.0
Total or Average		539,388	42.2	–	22.6

requirements. The relative frequency of the percentage of nodes with MPH per H-category was also calculated (Figure 2). Sub-standard pressures were found in all but one model. About 17% of all nodes analysed in this study (88,928 nodes) had minimum pressures below the design criterion of 24 m during peak hour flow conditions and 36,139 nodes were found with MPH < 12 m, which represents 6.7% of all nodes. In contrast to the sub-standard pressures mentioned above, about 13% of the nodes had residual pressure heads in excess of 72 m during peak hour demand, which is an indication of poor pressure management.

DISCUSSION AND FUTURE RESEARCH

The nodes where MPH criteria were not met could be assumed to represent the consumers serviced by those systems, implicating ~17% of all consumers. The finding is similar to the reported ~13% of urban water users in China who receive water at inadequate pressure (Browder 2007). Ghorbanian *et al.* (2016) noted that the frequency, duration, and intensity of pressure violations are relevant, but continue to ask the question, 'What kinds of pressure transgressions are most crucial to system performance and economics and what kinds are merely inconvenient?' While this study sheds some light on the extent of occurrence of sub-standard pressures in South African distribution systems, additional research is needed to understand the impact of those

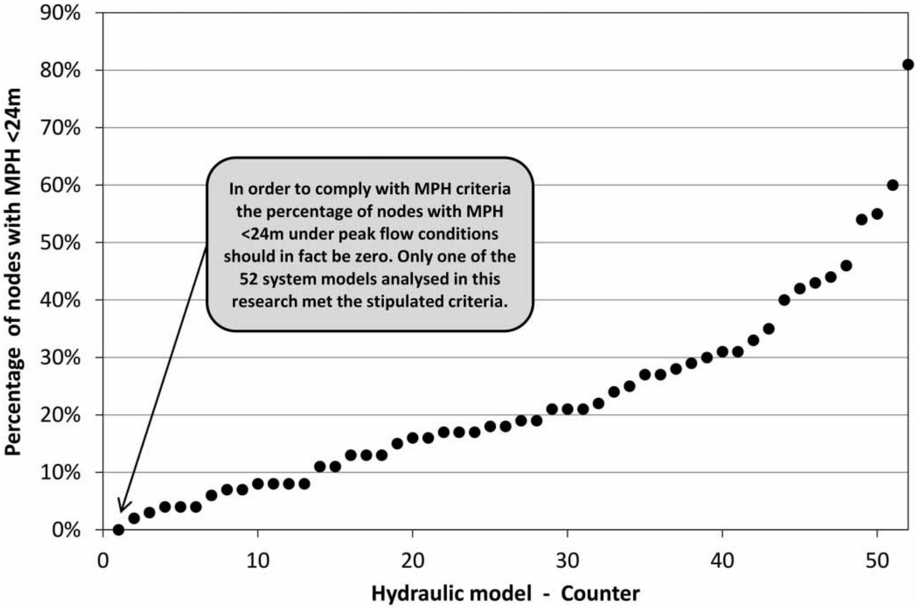
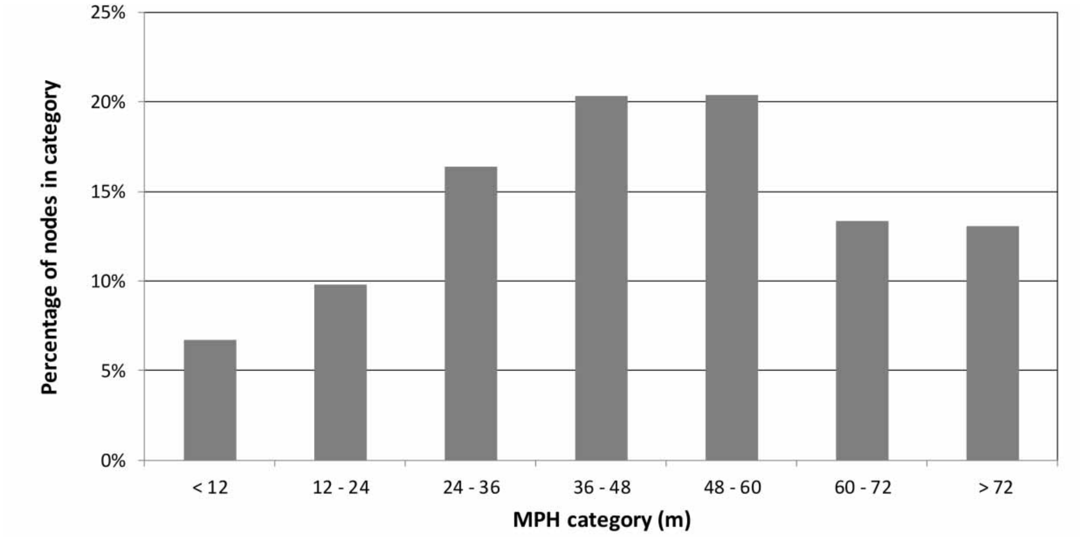


Figure 1 | Percentage of nodes in each of 52 models with MPH < 24 m – ranked small to large.



MPH category	< 12	12 - 24	24 - 36	36 - 48	48 - 60	60 - 72	> 72
Number of nodes	36,120	52,808	88,253	109,675	110,057	71,997	70,478
% of nodes	6.7%	9.8%	16.4%	20.3%	20.4%	13.3%	13.1%

Figure 2 | Relative frequency histogram of MPH for all nodes.

events; are they merely inconvenient or are they seriously compromising system performance and service delivery?

Relatively low system pressures may be intentional (e.g., for leakage reduction), or unintentional (e.g., due to problems such as financial constraints that prevent system upgrades). The authors are of the opinion that sub-standard pressures in the study area are unintentional and are the result of various challenges faced by water service providers in South Africa. It would be necessary to further research and better understand the reasons for sub-standard pressures in the systems reported on in this paper.

However, a relatively stringent MPH requirement, such as the 24 m currently used, may lead to overdesign and overspending on infrastructure when compared to a reduced MPH value. The results of this study suggest that the MPH criteria of 24 m may possibly be too conservative for South African systems. In contrast, the results also report relatively high pressures in certain parts of the systems, far in excess of the minimum requirement. The results show the need for better pressure management at both high and low ranges, but how low could the MPH requirement possibly be set?

A system pressure head of $\geq$10 m is needed for operation of some typical household appliances. Lowering the standard to 10 m, in line with Ofwat (2016), may be acceptable and would lead to some advantages, but customer outreach would be needed. If the standard were lowered to 10 m, proactive management would be needed because even small reductions below 10 m may have a larger risk in terms of system performance and effective service delivery than reduction to just under <24 m. The consequences of MPH between 10 m and the current minimum requirement of 24 m are limited to longer waiting times for filling of containers (baths, basins, water bottles, etc.) and less efficient irrigation systems. The consequences of MPH values decreasing to below 24 m, but not below 10 m, are therefore not considered to be insurmountable.

Reduced criteria for MPH have some clear advantages. In a South African case study, a cost saving of 32.5% on required upgrading of infrastructure was found when reducing the design standard from 24 m to 15 m in a particular urban system (Strijdom 2016). Future research is needed to investigate the financial benefits of dropping to (say) 15 m or 10 m, such as avoided or postponed infrastructure cost, reduced operations and maintenance cost, lowered leakage and lower pressure-driven demand.

In contrast, the negative impacts also need to be well researched. At the extreme when no residual pressure remains in the system (or parts of the system), intermittent supply results. Negative impacts of intermittent supply on a distribution system have been reported to include water quality degradation and increased pipe breakage (Kumpel & Nelson 2016). Intermittently supplied systems clearly violate any MPH criteria and are undesirable. However, some problems relating to intermittently supplied systems may apply to systems with relatively low pressure as well.

CONCLUSION

This research addressed the prevalence and extent of substandard pressures by using hydraulic models of potable WDS for 71 South African towns. Approximately 16.5% of modelled nodes analysed as part of this research experienced peak hour pressure heads below the current design criterion of 24 m, with only one system fully meeting the criterion. In contrast, the results also show that relatively high minimum pressures can be experienced on average in the systems, since the system would have been designed to comply with MPH > 24 m at the single most critical node during the most extreme peak hour demands (1 hour in a year equates to ~0.01% of the time). About 13% of the nodes had MPH in excess of 72 m. The results are an indication of poor pressure management, with regards to relatively low and also relatively high pressures.

The philosophy of designing for the theoretical peak hour demand condition at the most critical node leads to a system where all nodes would experience MPH in excess of the criteria for more than ~99.99% of the time. The South African criterion for MPH could possibly be relaxed, but not before benefits are quantified and implications are better understood. Future research is needed to investigate the issues raised and alternatives for practical application.

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