View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by AJOL - African Journals Online

Evaluation of minimum residual pressure as design criterion for South African water distribution systems

HE Jacobs* and JL Strijdom
Department of Civil Engineering, University of Stellenbosch, Private Bag X1, Matieland, 7602, South Africa

Abstract

The South African civil engineering fraternity has grown to accept 24 m as the design criterion for minimum residual pressure in water distribution systems. However, the theoretical peak demand in many systems has increased beyond the point where minimum residual pressure exceeds 24 m – at least according to hydraulic models. Additions of customers to existing supply systems have led to increased peak flows with time, often without infrastructure upgrades to internal reticulation. Increased flows imply reduced pressures. This is not necessarily a concern: peak flow conditions rarely occur in a supply system and also, customer complaints often act as a first sign of 'low pressures'. No complaints imply 'no low pressures'. The researchers analysed hydraulic models for 14 different towns in 5 municipal areas of South Africa, including 2 large metros, to identify the minimum residual pressures currently expected. The results include almost 55 000 model nodes and show that about 20% of the nodes in the distribution systems analysed have pressures of below 24 m, while pressures of below 14 m are not uncommon. Whether this relatively common occurrence of low pressures under modelled peak demand is found in practice is not known at this stage. A new guideline for minimum residual pressure based on previous criteria and results from this study is presented, noting that a physical lower limit of about 10 m water pressure is specified in home appliance specifications.

Keywords: water distribution system, residual pressure, peak flow, design standard

List of abbreviations and acronyms

AADD	-	average annual daily demand
AFU	-	automatic flushing urinal
DDA	-	demand driven analysis
H	-	residual pressure head (measured in m water)
HDA	-	head-dependent analysis
IPF	-	instantaneous peak factor
MPH	-	minimum pressure head
PDF	-	peak day factor
PHF	-	peak hour factor
PWF	-	peak week factor
WDS	-	water distribution system
NWCA	-	National Water Consumption Archive

Introduction

Motivation

The reasoning behind the stipulation of a minimum pressure requirement during water distribution system (WDS) design is customer satisfaction. A 'too low' pressure head would not be acceptable and could result in numerous customer complaints. In addition it could lead to operation and maintenance problems, with cost implications if equipment is damaged (e.g. pipe collapse due to negative pressure).

This paper was originally presented at the 2008 Water Institute of Southern Africa (WISA) Biennial Conference, Sun City, South Africa, 18-22 May 2008.
* To whom all correspondence should be addressed.
☎ +2721 808 4059; fax: +2721 808 4351;
e-mail: hejacobs@sun.ac.za

The pressure in a WDS is at a minimum when the flows and subsequent head losses in the pipes are at a maximum – a state termed 'peak demand'. On the other hand, the pressure is a maximum when the flow is at a minimum – normally at night-time while most consumers are asleep and industries are shut down. Despite pressure management initiatives and subsequently reduced leaks (McKenzie and Bhagwan, 1999) being valuable and effective, the minimum residual pressure in reticulation systems during peak demand conditions is used as a design criterion to size infrastructure. The significance of this criterion is often neglected locally in South Africa. The minimum pressure criterion is a significant driver of infrastructure cost and is the focus of this study.

Minimum residual pressure as design criterion

The residual pressure head (H), measured in metres, is used in this text to denote 'water pressure'. For the purpose of this text the minimum value of H under peak demand conditions is simply termed the 'minimum pressure head' (MPH). The minimum value of H occurs under peak demand conditions. The resulting peak-hour flow is used commonly in South African WDS design.

The MPH could be described as the lowest pressure at the most critical demand node in a WDS under maximum demand. These critical low-pressure nodes are normally the ones at relatively high elevations and relatively far from the supply points. During hydraulic modelling of water networks such critical 'low-pressure' nodes are identified and are then used by analysts as baseline values to ensure that minimum criteria for H are met throughout the entire network. Of course, high-pressure nodes are also viewed as critical nodes during system analyses, but these do not form the focus of this study.

The South African criterion for the MPH is a fixed value of 24 m. An increased MPH stipulated in design guidelines would result in an increased infrastructure capacity requirement, based on hydraulic model results, with subsequent increased capital expenditure in the construction phase. The MPH should be viewed as a critical parameter in the design – and eventual cost – of a WDS.

The results of this study are useful in view of compiling a new guideline criteria for MPH that is more appropriate for practical application in South Africa than the current 24 m. This investigation is the first report on minimum theoretical residual pressures in existing South African WDSs under peak demand.

Historical overview of South African design criteria

A brief history of design criteria for the MPH in WDSs in South Africa shows that 24 m has long since been the norm, despite some changes to the criteria over the years.

The first reported MPH criteria in South Africa, traced during this literature review, is about 50 years old (Leslie, 1957) and suggests an 'absolute minimum' of 12 m (reported as 40 ft) for low-income and 15 m (reported as 50 ft) for high-income areas. These values were apparently increased with improved standards of living during the 1970s. By the mid-1970s the MPH criterion published in various guidelines (Turner et al., 1977; Gebhardt, 1975; TPA, 1976) had increased to 25 m. The criterion of H > 24 m was included again in a popular guideline – commonly referred to as the 'Red Book' – that remains in general use to this day (CSIR, 1983; CSIR, 2003).

The wide publicity and use of the latter document series between 1983 and 2003, combined with the fact that the three last published MPH criteria prior to 1983 were either 24 m or 25 m, has resulted in the South African civil engineering fraternity generally accepting 24 m as the design criteria for MPH. Without further deliberation about whether it is the only or best value, 24 m is considered to be the most common South African design criteria for MPH in reticulation systems. It is used as a boundary point for categorising H-values in this study.

Scope and limitations of the study

Scope

Numerous South African WDSs were analysed by GLS Consulting (GLS, 2008) over the past few years as part of the drive by government to eradicate ongoing supply deficiencies. All these hydraulic models were available to the project team for further analysis. The scope of this research project was limited by financial and time constraints and only some of the systems could be scrutinised for use in this project.

Despite these constraints the hydraulic models of WDSs in 14 different towns, located in 5 municipal areas were analysed as part of this study. Some of these were split into individual pressure zones resulting in detailed statistical analyses of 35 different water distribution zones. Statistical analysis of a few large networks (e.g. Pretoria and Springs) comprised all pressure zones in one analysis, while others were split into separate pressure zones. The latter allowed the team to investigate the results for individual pressure zones even within one suburb. Not much could be learned at this stage from the analysis at the higher resolution of individual pressure zones.

The results of hydraulic network analyses comprising a total of 54 611 model nodes were included in the study. The two largest networks in the data set are Pretoria with 37 744 nodes and Springs with 6 074. The remaining 33 network zones analysed at pressure-zone scale included fewer nodes. Despite a relatively large number of nodes included in the analysis, the study is limited geographically and does not provide country-wide coverage.

Fire flow

Fire flows are often a more stringent requirement in the design of a WDS than peak demand. In this study it was considered appropriate to address the normal peak flow condition first, particularly since the resulting H-values were found to be insufficient compared to the design criteria of 24 m for peak flow. A similar approach was adopted by Buchberger et al. (2008) who considered fire flow to be exempt as the primary criterion for sizing pipes in assessing self-cleansing pipe velocities in municipal distribution systems.

The most common South African guidelines stipulate that demand for fire flow should be added to the peak hourly flow in a network. It is unlikely that a fire would occur at the same time as the peak hourly demand, but of course this would be possible. In North America, for example, this probability is deemed to be too small to be considered in design. Investigation into the financial risk due to damages and risk to human life due to fires in networks has recently been investigated (Filion et al., 2007; Jung and Filion, 2008), but its inclusion here was considered to be beyond the scope of this investigation. Future work could address fire-flow criteria for MPH in combination with the normal MPH requirement, focused on in this study.

Verification of models and possible future calibration

Models used in this study were verified by means of a monthly water balance. The process entails comparison of the monthly bulk meter readings to monthly water sales for each water zone. This is considered to be a limitation in that actual peak flow and pressure were not recorded during this study via pressure transducers and data loggers for precise model calibration. The measurement and logging of pressure at critical nodes in each network is beyond the scope of this study due to time and financial constraints. This was not considered to be a problem in view of obtaining meaningful results, because the hydraulic models and stipulated criteria for MPH are applied in the same manner in practice during the design phase of a new WDS.

To calibrate the models against measured H-values a large number of high frequency pressure and flow loggers would be required for a relatively long time period to ensure that the peak flow would be successfully recorded. A logging frequency of 2 min has been proposed before for service connections to capture the peak flow, while 30 min would suffice for bulk pipelines (Johnson, 1999).

Methodology

Selection of WDS zones for analysis

The selection of WDS zones for this study was based on available data and subsequent subjective judgement by the authors and was the first step toward obtaining and comparing system results. A relatively large number of hydraulic models were available to the research team initially and could be used in future to extend

Available on website http://www.wrc.org.za
ISSN 0378-4738 = Water SA Vol. 35 No. 2 (Special WISA 2008 edition) 2009
ISSN 1816-7950 = Water SA (on-line)

the work. These hydraulic models would require future verification of model topology and loads. However, only some systems that met stringent criteria were selected for this study.

Criteria that were considered during the selection process included:

- Long-term involvement by GLS (Consultants) with the particular WDS, the client(s) and the system model development
- A comprehensive knowledge of the WDS topology and hydraulic characteristics
- The availability of an up-to-date and accurate system model with regards to model topology
- A load case that reflects the present day peak hour demand scenario as accurately as possible (derived from actual metered information)
- Spatial distribution of systems covering different areas of the country, ensuring inclusion of some WDSs from the summer rainfall region in Gauteng province and some from the winter rainfall region in the Western Cape Province
- Selection of WDSs from large urban metropolises (e.g. Pretoria and Springs), small towns (e.g. Malmesbury) and holiday towns with a significant influx of holiday makers and significant peak flows in relation to the AADD (e.g. Hermanus and Stilbaai)
- Availability of client-feedback records with regard to complaints during times of low pressure.

Demand and peak flows

In South Africa demand-driven analysis (DDA) is the norm in hydraulic modelling of a WDS. With DDA the demand at each node is fixed. In reality, demand discharge at a node depends on the pressure head available at the node, which in turn depends on the node discharge. This non-linear coupling between demand and pressure head can be modelled with head-driven analysis models that respect the relationship between head and flow (Tanyimboh, 2008; Giustolisi and Laucelli 2007; Trifunović and Vairavamoorthy, 2008). In this study the researchers opted to use the locally conventional DDA.

The pressure head at any point in the system is a function of the flow, which in the hydraulic model is a function of the average demand and peak factor. The peak factor is the ratio of peak flow to average annual flow, termed the annual average daily demand (AADD) in South Africa. For example, designing a water network to meet the MPH criteria of 24 m at node X 'under theoretical peak demand' in the system would imply that MPH > 24 m at node X during all other flow scenarios.

The concept of an 'instantaneous' peak factor (IPF) was first published in 1983 and it remains in use locally (CSIR, 1983; CSIR, 2003). No explanation is provided in that publication as to the frequency implied by the term 'instantaneous demand'. Later studies reported that the IPFs were conservative (Van Vuuren and Van Beek, 1997; Booyens and Haarhoff, 2000). Peak factors presented by Vorster et al. (1995) for Gauteng are the only published values available in South Africa as alternative to the IPF; a table is provided with peak-week- (PWF), peak-day- (PDF) and peak-hour factors (PHF). The peak-hour flow, determined by multiplying the AADD with the PHF, is commonly used in South Africa to represent the peak flow scenario. Subsequently, these PHFs are widely used by specialist consultants instead of the IPF. The peak factors by Vorster et al. (ibid.) were used in this study to calculate the peak hour flows and are compared to the corresponding 1983 values in Table 1.

TABLE 1
Peak factors for WDS analysis in South Africa

Land use description	Guideline by Vorster et al. (1995)				Equivalent IPF, CSIR (1983)
	AADD (kℓ/d)	PWF	PDF	PHF	
Low cost housing	<1000	1.50	1.90	3.60	22 → 4 (A)
	1000 - 5000	1.40	1.80	3.40	4
	5000 - 10000	1.35	1.70	3.30	4
	10000 - 15000	1.30	1.50	3.20	4
	15000 - 20000	1.25	1.40	3.10	4
	>20000	1.25	1.40	3.00	4
Residential	<1000	1.80	2.20	4.60	45 → 4 (A)
	1000 - 2000	1.65	2.00	4.00	
	2000 - 5000				4
	5000 - 10000	1.50	1.80	3.60	4
	10000 - 15000	1.40	1.60	3.50	4
	15000 - 20000	1.35	1.50	3.30	4
	>20000	1.30	1.50	3.00	4
Business Commercial Industrial	<2000	1.45	1.70	3.30	45 → 4 (A)
	2000 - 5000				4
	5000 - 10000	1.30	1.60	3.15	4
	>10000	1.25	1.50	3.00	4

Notes: *A) The IPF varies linearly with AADD (max IPF at AADD→0) when plotted on a log-normal scale*

Hydraulic models

Hydraulic models chosen for this project were analysed using the commercial software package Wadiso 5.0 (GLS, 2008), which is based on the EPANET engine. All results produced were based on steady state demand-driven analysis of the peak hourly flow scenario.

Existing operational scenarios were selected for hydraulic analysis. Thus, the system load that represents the current (present day) water use was applied in each case. Vacant plots were thus considered to have no water demand. Each system was modelled at a relatively high resolution (large number of modelled nodes), with each occupied stand's measured water demand being allocated to the nearest modelled node. This results in populated nodes representing a cluster of well-distributed parcels (properties) in each pressure zone. The models contain sufficient nodes in order to ensure statistical significant coverage of the entire area. In other words, one node represents relatively few consumers that were spatially allocated to hydraulic model nodes via an automated GIS-based routine.

H-value categories

In order to investigate the distribution of pressure in the hydraulic network models, it was necessary to arbitrarily set boundaries for categorising H. This selection of boundaries was subject to sufficient data points being allocated to each category and also to upper (H < 120 m) and lower limits (H > 0 m). Although pressures in excess of 120 m are found in some extreme cases, these pressures were allocated to a single category, since high pressures were not the focus of this study. Instead, the categories were selected to examine how 'low pressures' are encountered.

It was considered appropriate to select 24 m as the starting point for categorisation, simply because this value is viewed as the local 'design standard'. It was considered a priority to become *au fait* with H-values slightly above and all values below

24 m. Using 24 m as a starting point, a trial-and-error process led the research team to select the boundary values of 4 m, 14 m, 24 m, 34 m, 44 m and 54 m for the purposes of this study. The selection of these boundary values enabled the research team to gain knowledge about:

- $H \leq 4$ m, representing extremely low pressure that is expected to be highly unlikely or erroneous (thus requiring verification of model topology and loads)
- 4 m < $H \leq$ 14 m, that could be viewed as 'insufficient' since the values in this range generally fall below the minimum pressure requirement of some appliances
- 14 m < $H \leq$ 24 m – seemingly acceptable pressures, but less than the MPH criterion
- H > 24 m – acceptable pressure according to existing guidelines divided into three categories.

Resolving negative values for H

In view of recent advances encouraging reliability analysis of water systems (Filion et al., 2007; Van Zyl and Haarhoff, 2007) and HDA (Tanyimboh, 2008; Giustolisi and Laucelli 2007; Trifunovic and Vairavamoorthy, 2008), the use of peak factors for estimating peak water demand in a DDA could be viewed as a limitation. However, the availability of monthly water-meter data on a large scale in the National Water Consumption Archive (NWCA), recently compiled in South Africa (Van Zyl and Geustyn, 2007), makes use of estimated peak demand based on these AADD-values the practical choice for this study. In fact the peak factors are based on the AADD, derived by taking the average of the most recent 12 months' readings. All networks analysed as part of this work make use of peak flows based on the AADD, which in turn is obtained from measured monthly water meter readings, such as those recorded in the NWCA. The method for obtaining AADD values from treasury systems has been widely employed in other studies (Jacobs et al., 2004; Jacobs, 2007; Van Zyl et al., 2008). Despite some limitations the method was considered the best choice for estimating demand and subsequent peak flows in this study.

In some of the networks analysed, application of the stipulated peak factors as per design criteria (Vorster et al., 1995) would have led to negative values for H at some points in the hydraulic models. Such cases are considered to be the result of over-estimated peak factors. To compensate for the over-estimated peak factors the latter were reduced incrementally until a 'realistic' minimum of H>0 was reached for all nodes. The latter was only done in select areas of Pretoria after careful scrutiny of the hydraulic model to ensure the accurate topological description of the actual system.

Minimum pressure requirement for some appliances

Some end-uses require a minimum pressure to operate, thus setting a physical lower limit for H in water networks. The question immediately arises, 'What is this lower limit?' If such a value were to exist it would dictate the MPH required in a system, thus justifying a brief review of appliance specifications.

Various domestic appliances require a minimum pressure to operate satisfactorily. A few examples of end-users with a minimum pressure requirement are summarised in Table 2.

Furthermore, sufficient pressure is needed to ensure that containers are filled in a 'reasonable' time when running taps are employed, e.g. for drinking water (no value is attached to this requirement for the moment due to it being somewhat subjective).

TABLE 2
End-user appliance minimum specifications

<table>
<tr><th>Appliance</th><th>Minimum required pressure head</th><th>Comments</th></tr>
<tr><td>Pop-up irrigation systems</td><td>H ≥ 20 m</td><td>The installation of a small booster pump in the irrigation system is recommended by suppliers if this pressure is not available</td></tr>
<tr><td>Washing machines and dish washers</td><td>H ≥ 10 m</td><td>This pressure is used as a typical customer guideline by local furniture suppliers</td></tr>
<tr><td colspan="2">Pressure flush toilets</td><td rowspan="3">Commercially known in South Africa as "Flush Master" toilets; relatively uncommon in SA</td></tr>
<tr><td>Back entry type</td><td>H ≥ 15 m</td></tr>
<tr><td>Top entry type</td><td>H ≥ 20 m</td></tr>
</table>

The requirement for pop-up irrigation systems tops the list with $H \geq 20$ m, but this is not considered critical by the authors in view of a minimum reticulation network pressure requirement, because such personal irrigation systems are easily boosted by small pumps at an insignificant cost to the owner. Irrigation systems are often boosted in this manner despite the availability of sufficient system pressure. This is particularly true when an alternative personal on-site water resource (e.g. borehole water, greywater or rainwater) is used for garden irrigation in addition to municipal supply.

Pressure flush toilets require about 15 m pressure to operate effectively. However, considering the fact that pressure flush toilets are not very common in South Africa and could be replaced in critical areas with cistern-type flush toilets if the need arises, the MPH-requirement for toilets could be put aside for the moment.

The 10 m requirement for washing machines and dishwashers remains. Some sources report lower H values for specific washing machines and dishwashers ($H \geq 8$ m). Also, some appliance manufacturers supply custom-designed equipment able to operate at even lower pressures, but such devices are an exception to the rule and are unlikely to be used widely by consumers in South Africa.

From the information available it is apparent that a system pressure of less than 10 m could be regarded as insufficient at present in view of appliance requirements in residential areas of South Africa.

Schools and other public buildings often make use of automatic flushing urinals (AFU) or pressure-flush toilets as is the case for domestic use. AFUs are considered to be old and are banned in many areas (e.g. Overstrand Municipality and the City of Cape Town) due to their inefficient use of water. In limited cases these devices are still operational, but are not considered a driver of the MPH-criteria for the purpose of this study.

Agricultural crop irrigation in serviced areas would require an MPH for efficient irrigation of crops. In some cases water is used for crop irrigation on either a private or commercial scale within urban areas and such areas would have to be identified separately in guidelines for MPH in networks. In such cases the irrigation system is designed to ensure a certain application rate (flow rate) and is dependent upon the supply pressure in the water system.

Available on website http://www.wrc.org.za
ISSN 0378-4738 = Water SA Vol. 35 No. 2 (Special WISA 2008 edition) 2009
ISSN 1816-7950 = Water SA (on-line)

A head lower than required would result in two problems:

- Low application rates and insufficient water reaching the crops
- The irrigation radius of sprinkler systems would be reduced by the low pressure in comparison to design values resulting in crops far from the irrigation point receiving no water at all.

However, this type of water use is limited in South African urban areas and it is considered to fall beyond the scope of this study.

Statistical analysis

Statgraphics Centurion XV was used by the team to conduct the statistical analyses. Each input data file comprised hydraulic model results (node output tables) exported from the software package Wadiso Version 5.4.

Presentation of results

In presenting the results, the focus is placed on summary statistics, including the sample size, average, standard deviation, minimum- and maximum values. The frequency and cumulative relative frequency of data in different H-categories are used to illustrate how the modelled values for H relate to the MPH-design criteria. The focus of this study is on the pressure regions near or below 24 m.

Customer behaviour indicative of low pressure

A 'too low' pressure head would result in numerous customer complaints. This study identifies numerous such areas. Despite this finding few customer complaints were reported by water service providers in these particular areas and the customers seem to accept such low pressures. Presuming the hydraulic models are accurate, the lack of complaints may be a result of the following factors:

- The consumers might be entirely unaware of the low-pressure state lasting for a relatively short time
- They could be ill-advised on the standards of pressures that they ought to be experiencing according to the current design criteria
- They are accepting the lower pressures because they simply do not need higher pressures to perform their domestic everyday water-use tasks.

Whatever the reason, the relatively low modelled residual pressures do not correlate strongly with a high number of customer complaints.

For medium- to high-income residential areas, the most likely reason for customer complaints would arise from failure of certain domestic appliances or irrigation equipment to operate, while for lower-income residential areas complaints are more likely to be filed once no water flows from the tap.

Results

Summary statistics

Table 3 includes the summary statistics of each model run. From the table it is clear that the selection criteria and method of analysis allowed for great variation in the number of nodes in each network zone.

Frequency histograms

A frequency histogram of the average residual system pressure under peak demand in all zones is shown in Fig. 1. The average pressure is obtained by taking the average pressure of all model nodes in each zone's hydraulic model during peak flow. Most systems analysed are found to have 30 m < $H_{ave} \leq$ 40 m, with H_{ave} < 20 m and H_{ave} > 50 m being less significant. The histogram

TABLE 3
Summary statistics of all networks analysed during this study

Town/City name	Municipality name	Pressure zone name [A]	Sample size (nodes)	Average H (m)	% Nodes with H < 24 m
Hermanus	Overstrand	Fisherhaven HL	56	35.4	42.9
Hermanus	Overstrand	Fisherhaven LL	306	28.2	34.3
Hermanus	Overstrand	Franskraal	272	31.2	21.0
Hermanus	Overstrand	Hawston	419	30.2	19.8
Hermanus	Overstrand	H-Heights	92	40.7	10.9
Hermanus	Overstrand	Hermanus cetral	788	20.5	84.8
Hermanus	Overstrand	Kleinmond	774	38.0	12.8
Hermanus	Overstrand	Northcliff	56	32.1	7.2
Hermanus	Overstrand	Onrus	511	42.3	1.2
Hermanus	Overstrand	Pringle Bay	268	36.4	6.3
Hermanus	Overstrand	Rooiels	75	44.2	4.0
Hermanus	Overstrand	Sandbaai	655	29.6	5.7
Hermanus	Overstrand	Stanford	67	28.9	47.8
Hermanus	Overstrand	Vermont	516	50.5	0.8
Hermanus	Overstrand	Voëlklip HL	283	15.2	89.8
Hermanus	Overstrand	Voëlklip LL	541	31.8	11.6
Hermanus	Overstrand	Zwelihle	517	29.0	18.4
Malmesbury	Swartland	Kleindam	413	38.3	15.0
Malmesbury	Swartland	Old golf club	259	56.9	8.1
Malmesbury	Swartland	Panorama	462	44.2	18.2
Malmesbury	Swartland	Prison	55	49.2	7.3
Malmesbury	Swartland	Wesbank	674	36.2	26.0
Malmesbury	Swartland	Wesbank2	170	27.0	28.2
Pretoria	Tshwane	All zones	37 744	51.2	8.8
Springs	Ekurhuleni	All zones	6 074	31.1	27.4
Stilbaai	Langeberg	Heidelberg Uitkyk	279	38.0	1.4
Stilbaai	Langeberg	Heidelberg	332	32.6	13.3
Stilbaai	Langeberg	Platbos1 - R	491	30.3	32.0
Stilbaai	Langeberg	Platbos2 - B	97	31.5	27.8
Stilbaai	Langeberg	Preekstoel	45	46.3	2.2
Stilbaai	Langeberg	River HL	319	51.7	58.0
Stilbaai	Langeberg	River LL	401	35.4	4.7
Stilbaai	Langeberg	River ML	186	33.9	42.5
Stilbaai	Langeberg	Stilbaai East	158	28.3	25.3
Stilbaai	Langeberg	Stilbaai West	256	19.5	80.1
Total / Average			54 611	35.6	24.2

Note:
A) HL = High level supply zone; ML = middle level supply zone; LL = Low level supply zone

suggests a normal distribution, but this is not considered significant in view of this study and was not assessed statistically.

It should be noted that 2 systems have an average pressure of less than 20 m, both being relatively small, while 7 others have 20 m < H_{ave} ≤ 30 m. This is considered a significant finding, because it illustrates that in some systems the average pressure head (H-value) is in the same order of magnitude as the existing guideline's criteria for MPH (H > 24 m).

With reference to the right-most column of Table 3, great variation is noted in the fraction of nodes in each system with H ≤ 24 m, expressed as a percentage of the total nodes in the particular system. In some systems practically all nodes have pressure in excess of 24 m, while in ten of the systems more than 25% of the nodes are found with H ≤ 24 m. In two systems about 80% of the nodes have 'insufficient pressure' (H ≤ 24 m) during peak flow.

Cumulative relative frequency

A more accurate picture is obtained when investigating the relative and cumulative frequencies. The categories for 4 m < H ≤ 14 m and 14 m < H ≤ 24 m represent values of pressure at nodes in the water network that are below the MPH stated in current design guidelines. Table 4 is a summary of the relative and cumulative frequency of model nodes with pressures in those categories where H ≤ 34 m. The values are expressed as a percentage of all model nodes in the particular system in each case. Three of the systems' results show H ≤ 34 m for practically all nodes in the system(s).

Discussion

Acceptability of pressures below design criteria

Some water consumers seem to find unacceptably low pressures (as per guideline criteria) quite acceptable. A serious look needs to be taken into current design criteria – or design philosophy for that matter. Could a more realistic

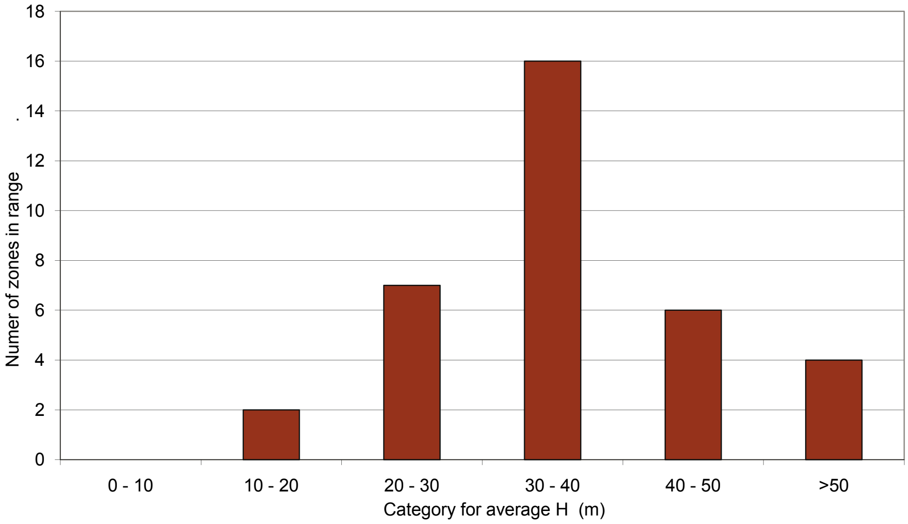

Figure 1
Frequency histogram of average system pressure

TABLE 4
Relative and cumulative frequency for H in all networks

Pressure zone description	Relative frequency (% of all nodes)					Cumulative frequency (% of all nodes)		
	< 4 m	4 - 14 m	14 - 24 m	24 - 34 m	> 34 m	< 14 m	< 24 m	< 34 m
Hermanus - Fisherhaven HL	1.8	30.4	10.7	3.6	53.6	32.2	42.9	46.4
Hermanus - Fisherhaven LL	0.0	2.6	31.7	34.6	31.1	2.6	34.3	69.0
Hermanus - Franskraal	3.7	5.2	12.1	21.7	57.4	8.8	21.0	42.7
Hermanus - Hawston	0.2	0.5	19.1	53.0	27.2	0.7	19.8	72.8
Hermanus - H-Heights	1.1	1.1	8.7	15.2	73.9	2.2	10.9	26.1
Hermanus - Hermanus cetral	0.0	7.1	77.7	15.1	0.1	7.1	84.8	99.9
Hermanus - Kleinmond	2.5	3.4	7.0	14.5	72.7	5.8	12.8	27.3
Hermanus - Northcliff	1.8	3.6	1.8	42.9	50.0	5.4	7.2	50.0
Hermanus - Onrus	0.4	0.2	0.6	16.1	82.8	0.6	1.2	17.2
Hermanus - Pringle Bay	0.4	0.0	6.0	29.9	63.8	0.4	6.3	36.2
Hermanus - Rooiels	4.0	0.0	0.0	8.0	88.0	4.0	4.0	12.0
Hermanus - Sandbaai	0.3	0.5	4.9	88.6	5.8	0.8	5.7	94.2
Hermanus - Stanford	11.9	32.8	3.0	1.5	50.7	44.8	47.8	49.3
Hermanus - Vermont	0.0	0.4	0.4	14.0	85.3	0.4	0.8	14.7
Hermanus - Voëlklip HL	5.0	40.6	44.2	9.9	0.3	45.6	89.8	99.7
Hermanus - Voëlklip LL	0.4	0.9	10.4	47.0	41.4	1.3	11.6	58.6
Hermanus - Zwelihle	0.0	1.0	17.4	69.4	12.2	1.0	18.4	87.8
Malmesbury - Kleindam	1.0	4.8	9.2	19.4	65.6	5.8	15.0	34.4
Malmesbury - Old golf club	0.4	3.1	4.6	3.1	88.8	3.5	8.1	11.2
Malmesbury - Panorama	4.6	5.4	8.2	14.9	66.9	10.0	18.2	33.1
Malmesbury - Prison	1.8	3.6	1.8	16.4	76.4	5.5	7.3	23.6
Malmesbury - Wesbank	2.8	10.2	12.9	18.6	55.5	13.1	26.0	44.5
Malmesbury - Wesbank2	0.0	14.1	14.1	51.8	20.0	14.1	28.2	80.0
Pretoria - All zones	0.0	2.6	6.2	10.8	80.4	2.6	8.8	19.6
Springs - All zones	0.0	2.8	24.6	38.2	34.4	2.8	27.4	65.6
Stilbaai - Heidelberg Uitkyk	0.4	0.4	0.7	22.9	75.6	0.7	1.4	24.4
Stilbaai - Heidelberg	1.8	4.8	6.6	28.3	58.4	6.6	13.3	41.6
Stilbaai - Platbos1 - R	9.6	8.4	14.1	22.8	45.2	17.9	32.0	54.8
Stilbaai - Platbos2 - B	0.0	0.0	27.8	35.1	37.1	0.0	27.8	62.9
Stilbaai - Preekstoel	2.2	0.0	0.0	2.2	95.6	2.2	2.2	4.4
Stilbaai - River HL	0.0	7.8	50.2	9.1	32.9	7.8	58.0	67.1
Stilbaai - River LL	0.5	1.0	3.2	31.7	63.6	1.5	4.7	36.4
Stilbaai - River ML	0.0	32.3	10.2	31.7	25.8	32.3	42.5	74.2
Stilbaai - Stilbaai East	9.5	3.2	12.7	30.4	44.3	12.7	25.3	55.7
Stilbaai - Stilbaai West	6.3	6.6	67.2	19.5	0.4	12.9	80.1	99.6

Available on website http://www.wrc.org.za
ISSN 0378-4738 = Water SA Vol. 35 No. 2 (Special WISA 2008 edition) 2009
ISSN 1816-7950 = Water SA (on-line)

TABLE 5 Proposed interrim criteria for minimum pressure head in water networks	
MPH criteria (m)	**Description**
H ≤ 12 m	Unacceptable pressure head - pressure too low
12 m < H ≤ 24 m	Low pressure head; acceptable under some circumstances
H > 24 m	Acceptable pressure head

approach to practical design, based on probabilistic principles be the way of the future, or will municipalities keep on spending money on unnecessary infrastructure upgrading?

The results of this study suggest that an improved comprehensive guideline for MPH is needed by the South African engineering fraternity. However, the results are not presented as a guideline *per se* due to the limited geographical coverage of the country, the lack of segregation by land use type and the lack of model calibration to measured peak flow. A robust interim guideline is instead presented.

The research suggests that about 20% of all nodes in a typical urban water supply system could be considered to have 'insufficient pressure' (compared to existing criteria). Thus, about 20% of all consumers in such a system could be experiencing 'insufficient pressure' during peak periods. Is this critical – would it be wise for a local authority to spend its valuable financial resources on improving the pressure in its existing water network by a few metres head to ensure that the criteria for MPH is met?

Firstly, a system pressure of less than the MPH criterion of 24 m is not considered to be a catastrophic system failure (fireflow requirement being exempt). Colombia, for example, stipulates only 15 m as MPH criterion in that country (Saldarriaga et al., 2008). In South Africa water infrastructure expenditure is traded off between upgrading systems to meet the MPH criteria and provision of new services to those who have none. Low pressure in an existing WDS could thus rather be viewed as 'inconvenient' to the consumer in view of predetermined expectation regarding service delivery. In contrast, neglecting the provision of potable water to those who do not have it in the first instance may entail a health hazard and may even be life threatening.

Secondly, the peak flow lasts for a very short time, say maybe an hour per year (Booyens and Haarhoff, 2000). Occurrence of a peak-flow event equal to the design theoretical peak flow is, per definition, highly unlikely. Problems arising from a lack of system pressure occur only during that short time span and do not have a long-lasting impact on human behaviour or health.

A comprehensive combined interim guideline criteria for MPH

Results of this study suggest that the current criterion of 24 m for MPH is too stringent, measured by the relatively few customer complaints in regions where modelled results suggest low pressures. Since 2004 engineering consultants GLS have included a category for H<15 m in their water master plan results in addition to H<24 m due to the high number of pipe elements where the pressure is in this region between 15 m and 24 m. The selection of 15 m was based on subjective judgment at the time and triggered this investigation.

An interim guideline criterion for MPH could be obtained by integrating the following available information:

- The 50-year old Leslie (1957) criteria (12 m & 15 m),
- The more recent CSIR (1983) criteria (24 m) and
- The physical limits placed on the system by appliance pressure (10 m)

This integration leads to a somewhat complicated criterion:

- MPH ≤ 10 m – unacceptable pressure head where some home appliances would not operate
- 10 m < H ≤ 12 m – a grey area of low pressure that is probably unacceptable
- 12 m < H ≤ 15 m – a grey area of low pressure
- 15 m < H ≤ 24 m – a grey area of low pressure that is probably acceptable
- H > 24 m – acceptable pressure head.

Bold simplification of the above is obtained by dropping some of the categories and being slightly conservative in the description, leading to the robust interim guideline criterion for MPH presented in Table 5.

Further research and collaboration with industry is under way to shed more light on the grey areas included as description in Table 5 for the category where 12 m < H ≤ 24 m.

Future work

Based on the above it is clear that an urgent need exists for the further expansion of this study. The results are still based on theoretical analyses and is likely to differ from what is actually observed in the field. Despite this being the first study of its kind in South Africa and almost 55 000 nodes being included, the scope of this study is not representative of South Africa as a whole.

Expansion of the scope of study

More WDSs need to be included in the study. The researchers intend to expand the current scope of the study by including WDSs from all the large municipalities of at least Gauteng, the Eastern- and the Western Cape.

Categorisation according to land uses

In 1957, criteria for MPH distinguished between two types of residential areas with separate MPH criteria for low-income and high-income areas (Leslie, 1957). Perhaps a guideline based on segregation should be reconsidered. A land-use based criterion for MPH could be categorised along the lines of various different land uses – information typically available from GIS database files. A land-use based criterion would allow greater flexibility for planners and engineers when applying this criterion in future. The large number of data points (nodes) available and the existing inter-connectivity between the hydraulic model nodes and GIS shape files suggests that a robust, land-use based criterion for MPH could be produced.

It may not be politically correct having separate design criteria for low- medium- or high income residential areas. Some might view this as designers erring to the side of discrimination, others might argue that there are indeed areas where consumers are less likely to make use of the various domestic appliances that require relatively higher pressures to operate. Therefore, providing such areas with 'too high pressures' that are not required not only leads to overspending on infrastructure, but also increases water leaks and the risk of pipe bursts.

Sensitivity analyses based on peak factors

Perhaps some of the hydraulic models overestimate the peak flow due to too high peak factors and thus underestimate H. A peak factor sensitivity analyses could be performed to investigate the rate of change in MPH for subtle changes in the peak factors used. Overestimation of peak flows due to high peak factors might lead to huge over-spending on infrastructure upgrading while (for the same AADD) underestimation of peak flows due to low peak factors might result in sub-standard pressures in the field for some consumers. A detailed study is therefore required to determine exactly how sensitive this adjustment to peak factors can be on peak residual pressures.

Reproduction of results based on different MPH categories

As mentioned previously, the MPH category boundaries used for this study were H = 4 m, 14 m, 24 m and 34 m. As the possibility exists that a substantial portion of the node pressure results may fall close to MPH category boundaries, a better picture can be obtained by running repetitions of the same analyses but with different MPH category boundaries. The results can furthermore be refined by repeating the analyses with more MPH categories.

Low-pressure area detail study

Due to the fact that the study was based on the actual measured monthly water demand combined with theoretical peak factors, it needs to be confirmed that the areas that indicate low pressures from the analysis are, in fact, actually experiencing low pressures in the field. This would obviously entail more than having discussions with the water service provider as they will only be aware of low pressures once they receive formal complaints. Complaints pertaining to low pressure are not necessarily always made by the consumers.

Interaction with consumers in the theoretical low-pressure areas as well as the implementation of pressure loggers would provide verification of these theoretically-based findings in the field.

Scenario cost analysis comparison

A complete cost analysis for the infrastructural upgrading requirements for all the systems in the expanded study mentioned above could be performed. These upgrading requirements must be based on complying with the current minimum design criterion of 24 m residual pressure during peak demand. A similar cost analysis must then be repeated for infrastructural upgrading requirements based on a set of new design criteria (yet to be compiled) and compared to the first cost analysis.

Conclusion

The current local guideline criterion of MPH > 24 m has been in place since about 1974. The aim of this study was to investigate the validity of this criterion by scrutinizing hydraulic models of selected South African WDSs. For this purpose a detailed investigation into hydraulic model results of 14 different towns and almost 55 000 model nodes in total was conducted. About 20% of model nodes were found to have MPH below the guideline criterion of 24 m. The variation between different systems is significant. Some zones have compliance of 99% nodes conforming to this criterion, with less than 20% in other network models (implying that more than 80% of the nodes in these systems have MPH of less than 24 m during peak-hour flow periods).

Despite this study showing, for the first time, that a significant percentage of the water users in a typical South African urban water supply network may be experiencing pressures under the current guideline criteria, few customer complaints were reported by water service providers in these particular areas. Many customers seem to accept such ‘low pressures’.

The first reported MPH criterion in South Africa (Leslie, 1957) suggested an ‘absolute minimum’ of 12 m for low-income and 15m for high-income residential areas. The results from this analysis are better described by the 50-year old criterion than the existing criterion of 24 m (that is 33-years old!).

A robust, interim guideline criterion for MPH in urban water networks is presented as a basis for further work. It could be used for immediate application in water master planning as a guideline for the MPH in a WDS.

Acknowledgements

The significant contribution to this work by Dr Leon Geustyn is greatly acknowledged. The authors also thank the various local authorities and their staff who made information available for this study and assisted with the lengthy process of data gathering, data capturing, hydraulic model compilation and the ongoing process of model verification, improvement and update. Also, credit is due to former researchers for publishing their results and in so doing providing industry with design criteria for minimum pressure over the years.

References

BOOYENS JD and HAARHOFF J (2000) Spitsvloei in Munisipale Waterverspreidingsnetwerke. Masters Degree Thesis. Rand Afrikaans University (now University of Johannesburg). June (2000).

BUCHBERGER SG, BLOKKER M and VREEBURG J (2008) Sizes for self-cleaning pipes in municipal water supply systems. In: Van Zyl JE, Ilemobade AA and Jacobs HE (eds.) *Proc. 10th Annu. Water Distribution Systems Analysis Conf. WDSA2008*. 17-20 August 2008, Kruger National Park, South Africa. 338-347.

CSIR (2003) 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.

CSIR (1983) Guidelines for the Provision of Engineering Services for Residential Townships. A report compiled for the Department of Community Development.

GEBHARDT DS (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. http://www.wrc.org.za/downloads/watersa/1975/Vol1No1/0011%20abstract.pdf.

FILION YR, ADAMS BJ and KARNEY BW (2007) Stochastic design of water distribution systems with expected annual damages. *J. Water Resour. Plann. Manage. ASCE* **133** (3) 244-252.

GLS (2008) Product information available online at URL: www.gls.co.za (Accessed May 19, 2008).

GIUSTOLISI O and LAUCELLI D (2007) More realistic water distribution network design using pressure-driven demands and leakages. In: Ulaniki et al. (eds.) *Proc. Computer and Control in Water Industry (CCWI) – Water Management Challenges in Global Changes*. Taylor and Francis Group, London. 177-183.

JOHNSON EH (1999) Short Communication: Degree of utilisation - the reciprocal of the peak factor. *Water SA* **25**(1) 111-115. http://www.wrc.org.za/archives/watersa%20archive/1999/January/jan99_p111.pdf.

JUNG BS and FILION YR (2008) Particle swarm optimisation of water distribution networks with economic damages. In: Van Zyl JE, Ilemobade AA and Jacobs HE (eds.) *Proc. 10th Annu. Water Distribution Systems Analysis Conf. WDSA2008.* 17-20 August 2008, Kruger National Park, South Africa. 429-436.

LESLIE R (1957) Water reticulation – records and standards. *Trans. S. Afr. Inst. Civ. Eng.* **7** (2) 74-77.

MCKENZIE RS and BHAGWAN J (2000) Managing unaccounted for water in potable WDSs: Recent software developments through the WRC. *Off. J. Inst. Mun. Eng.* **25** (1) 53-58.

SALDARRIAGA JG, BERNALA and OCHOA S (2008) Optimized design of water distribution network enlargements using resilience and dissipated power concepts. In: Van Zyl JE, Ilemobade AA and Jacobs HE (eds.) *Proc. 10th Annu. Water Distribution Systems Analysis Conf. WDSA2008.* 17-20 August 2008, Kruger National Park, South Africa. 803-813.

TANYIMBOH TT (2008) Robust algorithm for head-dependent analysis of water distribution systems. In: Van Zyl JE, Ilemobade AA and Jacobs HE (eds.) *Proc. 10th Annu. Water Distribution Systems Analysis Conf. WDSA2008.* 17-20 August 2008, Kruger National Park, South Africa. 803-813.

TPA (1976) Transvaal Provincial Administration: Recommended Guidelines for the Provision of Essential Services to Residential Townships – TPA Steering Committee for Municipal Services – Guidelines for Water Supply – Residential Townships, Pretoria, South Africa.

TRIFUNOVIĆ N and VAIRAVAMOORTHY K (2008) Use of demand-driven models for reliability assessment of distribution networks in developing countries. In: Van Zyl JE, Ilemobade AA and Jacobs HE (eds.) *Proc. 10th Annu. Water Distribution Systems Analysis Conf. WDSA2008.* 17-20 August 2008, Kruger National Park, South Africa. 129-141.

TURNER RB, BODE ECW, STANDER N and VAN DER MERWE C (1977) Guidelines for the Design of Water Distribution Pipe Networks. A Report by the University of Pretoria, South Africa, Department of Civil Engineering, Applied Hydraulics. November 1977.

VAN VUUREN SJ and VAN BEEK JC (1997) Her-Evaluering van die Bestaande Riglyne vir Stedelike en Industriële Watervoorsiening Gebaseer op Gemete Waterverbruike, Fase 1: Pretoria Voorsieningsgebied. WRC Report No. 705/1/97. South African Water Research Commission, Pretoria, South Africa.

VAN ZYL HJ, ILEMOBADE AA and VAN ZYL JE (2008) An improved area-based guideline for domestic water demand estimation in South Africa. *Water SA* **34** (3) 381-392. http://www.wrc.org.za/downloads/watersa/2008/July/2231.pdf

VAN ZYL JE and HAARHOFF J (2007) Reliability analysis of municipal storage reservoirs using stochastic analysis. *J. S. Afr. Inst. Civ. Eng.* **49** (3) 27-32.

VAN ZYL JE and GEUSTYN LC (2007) Development of a National Water Consumption Archive. WRC Report No. 1605/1/07. South African Water Research Commission, Pretoria, South Africa.

VORSTER J, GEUSTYN LC, LOUBSER E, TANNER A and WALL K (1995) A strategy and master plan for water supply, storage and distribution in the East Rand region. *J.S. Afr. Inst. Civ. Eng.* **37** (2) 1-5.