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Estimating residential water demand in southern Africa

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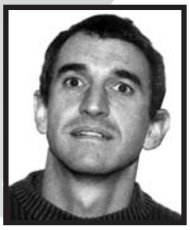
It is understandable that an easy method to obtain estimates of residential water demand is often used. These estimates are also extended to calculate peak demand and sewer flow, and impact an authority's water and sewer infrastructure budget and finally its expenditure. Guideline curves are presented in this paper that can be used to estimate annual average residential water demand based on stand size. The measured water consumption and stand size of more than 600 000 single residential stands were obtained. Treasury databases for Cape Town, Ekurhuleni, George, Midrand, Randfontein and Tshwane were analysed in detail and the results compared to similar work in Windhoek. The large number of records made it possible to conduct statistical analyses and to investigate the distribution of data for stand size intervals of 100 m^2. The water demand of similar sized stands in townships and suburbs could be compared. A strong relationship exists between the average annual water demand and stand size. The authors note that a model based on stand size has limited application only when better methods are not available.



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INTRODUCTION

Background

Stand size has been used to estimate residential water demand in South Africa since at least 1979 (Garlipp 1979; CSIR 1983). At a later stage it was recognised that residential demand estimates should preferably be based on actual water use per town as recorded by the Treasurer (City of Johannesburg 1989). Guidelines for the estimation of demand based on stand size are however still widely used and promoted (Austin 1995; CSIR 2003). A guideline based on stand size should only be used when more accurate methods are not available.

Until recent years custom analysis of the data was required, in other words, it was not possible to analyse the data programmatically, which is time consuming and not always economically feasible. Treasury systems contain a wealth of information, but closed database structures often obscure knowledge on the actual water demand required for analysis. The past decade has seen software developments that enable engineers to abstract and analyse water demand from treasury databases. It has subsequently become possible to abstract and analyse information from treasury databases for selected municipalities who have employed these software tools. In this manner water demand could be modelled more accurately. Results from such studies could also be used to construct guidelines for demand estimation based on stand size as a sole explanatory variable – a model with one explanatory variable, or independent variable, is termed a single coefficient model. Such guidelines can then be used in cases where more accurate methods are not affordable.

Motivation for new guideline and envelope curves

The most common South African guideline (CSIR 2003) dates from about 30 years ago and does not respect geographic location. Also, it is desirable to estimate the actual demand and then add an appropriate percentage of unaccounted for water (UAW) to that estimate. These aspects provided the motivation to update the stand size-based guidelines.

The average water demand guidelines (see fig 1) in the most recent publication of the so-called 'Red Book' (CSIR 2003) has remained unchanged since the first publication of the original guideline known as the 'Blue Book' (CSIR 1983). The curve appears to originate from work by the then Transvaal Provincial Administration (TPA 1976). Garlipp (1979) presented water demand estimates based on stand size that were less conservative than those originally included in the Blue Book, but these are not widely used.

It has been shown by various authors that water demand has a negative price elasticity, in other words water demand decreases with increases in price (Veck & Bill 2000; Van Zyl *et al* 2003). Over the past two decades consumers have increasingly appreciated water as a scarce and sought after commodity and for this reason it has become more expensive. It can be expected that the water demand of a residential stand would have been reduced over the years.

It has also long been recognised that garden irrigation requirements depend on factors influencing vegetation growth, such as rainfall and evaporation (Linaweaver *et al* 1963), which often vary significantly with geographic location.

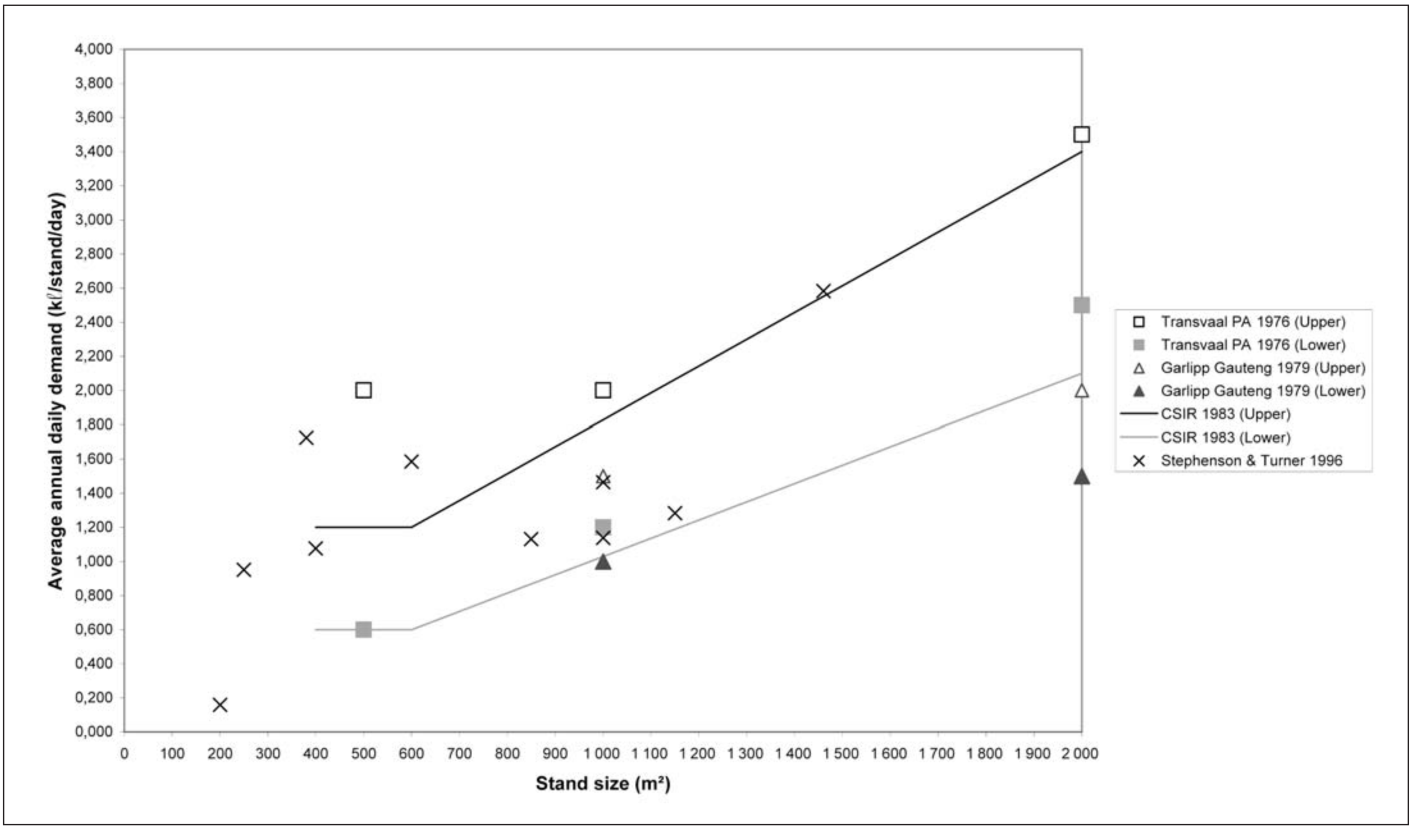


Figure 1 Available guidelines and previous work

METHODOLOGY

Engineering software used for analysis

The Swift commercial software package (GLS 2004) interrogates treasury databases and enables the user to analyse the recorded water consumption from individual consumer connections. About 20 municipalities have implemented Swift the past five years since it has become commercially available. As a further step the Swift records can be linked to the unique cadastral code of the Surveyor General (SG) to enable the user to view the geographical location relating to each treasury record in a GIS. The Infrastructure Management Query Station (IMQS) commercial software package is a GIS-based management tool and was used in this analysis to visually inspect certain aspects of the treasury records.

Selection of treasury databases

Towns chosen for the analysis were those that had implemented Swift, completed the SG code link and had implemented IMQS. Databases were selected on the basis of sufficient records to ensure a small statistical error. The following treasury databases were selected :

- *Ekurhuleni Metropolitan Municipality*: Alberton-Thokoza, Benoni-Daveyton-Etwatwa, Boksburg-Vosloorus, Brakpan, Germiston-Katlehong, Kempton Park-Tembisa, and Springs-Kwa Thema
- *Cape Town*: Blaauwberg, Helderberg, and Tygerberg (West, Central and South)
- *Other Gauteng*: Tshwane (Akasia, Atteridgeville, Centurion, Mamelodi, Pretoria, and Soshanguve), Randfontein and Midrand
- *Other regions*: George and Windhoek

The databases for Cape Town and Ekurhuleni were chosen for detailed analyses. Similar analyses had been conducted on Tshwane and Windhoek treasury data at the time, and these results are included for comparison. The databases for Randfontein, Midrand and George were also analysed as part of this investigation in order to improve the confidence for the Gauteng region and obtain an understanding of water demand in coastal regions with sustained annual rainfall.

Single residential stand selection

The selection of records pertaining to single residential stands from a large number of treasury records was the first step towards the new guideline curves. A stringent query was executed to select records exclusively for single residential stands. The query was used to select only those records from each treasury database that had the following attributes:

- The record is not flagged as vacant.
- The recorded value originates from a water meter that registers water use.
- The record is not flagged as a large water user – this would be one using >20 kℓ/day.
- The record is uniquely assigned to a stand (there is one meter per stand and vice versa).
- The record indicates an improvement value on the property larger than zero.
- The stand size is larger than 50 m² and smaller than 2 050 m².
- The land use category of the record is single residential.
- Any remaining duplicate record was removed from the selection.

The records extracted by means of this query include only those records in the selected size range that represent a single residential stand with inhabitants living in a dwelling and using water from a single metered water connection to the pressurised municipal supply system.

It is possible that the selection of single residential records from treasury data includes a few users that do not meet the desired specification due to erroneous entries in the treasury databases, but their effect on the result is considered to be insignificant.

The recorded water demand for some records correctly selected by means of the above query was high when compared to other records in the same stand size class. It was decided not to exclude these relatively large water users from the analysis, since it is possible that these stands' water consumption is justifiable, say for garden watering.

Stand type categories

In Ekurhuleni two types of stands – suburban and townships – could be categorised for each treasury database. Stand valuation and improvement value are possible parameters

Table 1 Number of single residential records selected for analyses

Cape Town		Ekurhuleni			Tshwane		Other	
Region	Records	Region	Suburb	Township	Region	Records	Region	Records
Blaauwberg	24 012	Alberton	15 022	7 189	Centurion	24 691	Randfontein	13 570
Helderberg	23 562	Benoni	13 989	17 409	Atteridgeville	13 344	Midrand	8 257
Tygerberg	69 457	Boksburg	22 972	24 274	Mamelodi	25 573	George (2000)	6 227
		Brakpan	7 447	0	Soshanguve	43 885	George (2003)	10 280
		Germiston	20 222	24 050	Akasia	7 209		
		Kempton Park	20 758	23 614	Pretoria	90 719		
		Springs	12 000	13 265				
Total	117 031		112 410	109 801		205 421		38 334

Table 2 Sample size, mean and estimated error on mean at 95 % confidence

Area (m^2)	Cape Town combined			Ekurhuleni combined					
				Suburbs			Townships		
	Records	AADD (kℓ/day)	Error @ 95 % (kℓ/day)	Records	AADD (kℓ/day)	Error @ 95 % (kℓ/day)	Records	AADD (kℓ/day)	Error @ 95 % (kℓ/day)
100	7 567	0,465	0,008	0	–	–	1 004	0,627	0,047
200	25 111	0,491	0,005	0	–	–	18 527	0,600	0,012
300	19 935	0,584	0,006	4 209	0,495	0,014	75 984	0,788	0,007
400	8 956	0,709	0,010	2 824	0,646	0,019	10 114	0,765	0,016
500	20 533	0,793	0,008	4 949	0,721	0,016	2 778	0,862	0,032
600	11 674	0,949	0,010	3 734	0,790	0,019	898	0,913	0,064
700	7 101	1,080	0,015	6 085	0,863	0,017	612	1,066	0,107
800	4 028	1,203	0,022	11 757	0,849	0,009	0	–	–
900	2 734	1,252	0,030	10 526	0,934	0,011	0	–	–
1 000	4 907	1,222	0,022	32 653	0,985	0,006	0	–	–
1 100	1 579	1,346	0,042	10 525	1,013	0,012	0	–	–
1 200	1 182	1,541	0,055	6 267	1,056	0,016	0	–	–
1 300	703	1,450	0,077	3 669	1,113	0,023	0	–	–
1 400	471	1,595	0,108	2 209	1,155	0,031	0	–	–
1 500	416	1,532	0,106	5 518	1,279	0,020	0	–	–
1 600	283	1,594	0,132	1 563	1,237	0,039	0	–	–
1 700	223	1,787	0,211	1 484	1,533	0,051	0	–	–
1 800	149	1,711	0,202	1 026	1,470	0,063	0	–	–
1 900	129	1,849	0,224	774	1,550	0,088	0	–	–
2 000	236	1,834	0,250	2 979	1,508	0,035	0	–	–
Total	117 917	–	–	112 751	–	–	109 917	–	–

that could be used to make the classification between suburbs and townships. However, these values are subjectively determined and cannot necessarily be transposed from one town to another. For this reason it was decided not to use the valuation as a criteria for selecting suburban and township stands from the records.

The IMQS software package was used to view the linkage of the treasury records to the SG cadastral information in GIS format and to subsequently classify stands into townships and suburbs based on knowledge of the areas. Some stands located along the township and suburban boundaries could not clearly be identified as township or suburban stands and were discarded from the selection to ensure that the two categories contain only discrete records. The results are presented with the legacy of segregated town planning. It might become necessary to update the results presented in this paper in future based on changing socio-economic composition and boundaries of suburbs and townships.

In the other treasury databases no attempt was made to categorise stands further by type, either because of the smaller number of records in a database or the fact that boundaries between township and suburban areas are blurred sufficiently to make such a classification inappropriate. This led to the final selection of records used for analysis as summarised in table 1.

Data period and calculation of the average annual daily demand (AADD)

All the treasury records include monthly water consumption per stand. Swift uses 12 months' values prior to the data extraction date to calculate the AADD. This calculated AADD was used for the analysis in each case.

The date of extraction from the treasury systems varied from July to September 2002 for the various Ekurhuleni datasets – for each dataset at least 12 months' values were included in the analysis. The extraction dates for other regions varied from December 1999 to July 2003, including at least 12 months' data in each case.

Stand size class

The stand size listed for each consumer in treasury databases was used without amendment. Sample size estimation suggested that the stand size range could be divided into 20 classes, each with a bound of 100 m^2 ranging from 100 m^2 (50–150 m^2) to 2 000 m^2 (1 950–2 050 m^2). The statistical sample size calculation was based on sufficient data points in each class to ascertain with 95 % confidence that the error on the mean will not exceed 10 %.

RESULTS

Combined databases

The three combined datasets for Ekurhuleni (suburb), Ekurhuleni (township) and Cape Town were analysed separately for each of the size classes, supposedly resulting in 60 datasets, three for each of the 20 size classes between 100 m^2 and 2 000 m^2. However, the whole matrix could not be filled due to a lack of records in some stand size classes. For Ekurhuleni suburban stands smaller than 300 m^2 and township stands larger than 700 m^2 too few records were selected and all were removed from the selection. Table 2 presents the sample size, mean value and estimated error for records included in the combined database analyses.

Frequency histograms and statistics for each of the 45 available datasets were calculated. The average AADD values were plotted against the centre value for the size class (eg 500 m^2 was used to represent the size class $450\ m^2 \le A < 550\ m^2$, where A is the stand size). The actual average stand size for each stand size class was calculated and found to be within 2 % of this centre value. The same procedure was repeated for two combined databases for George (one each for the years 2000 and 2003). The results are presented in figure

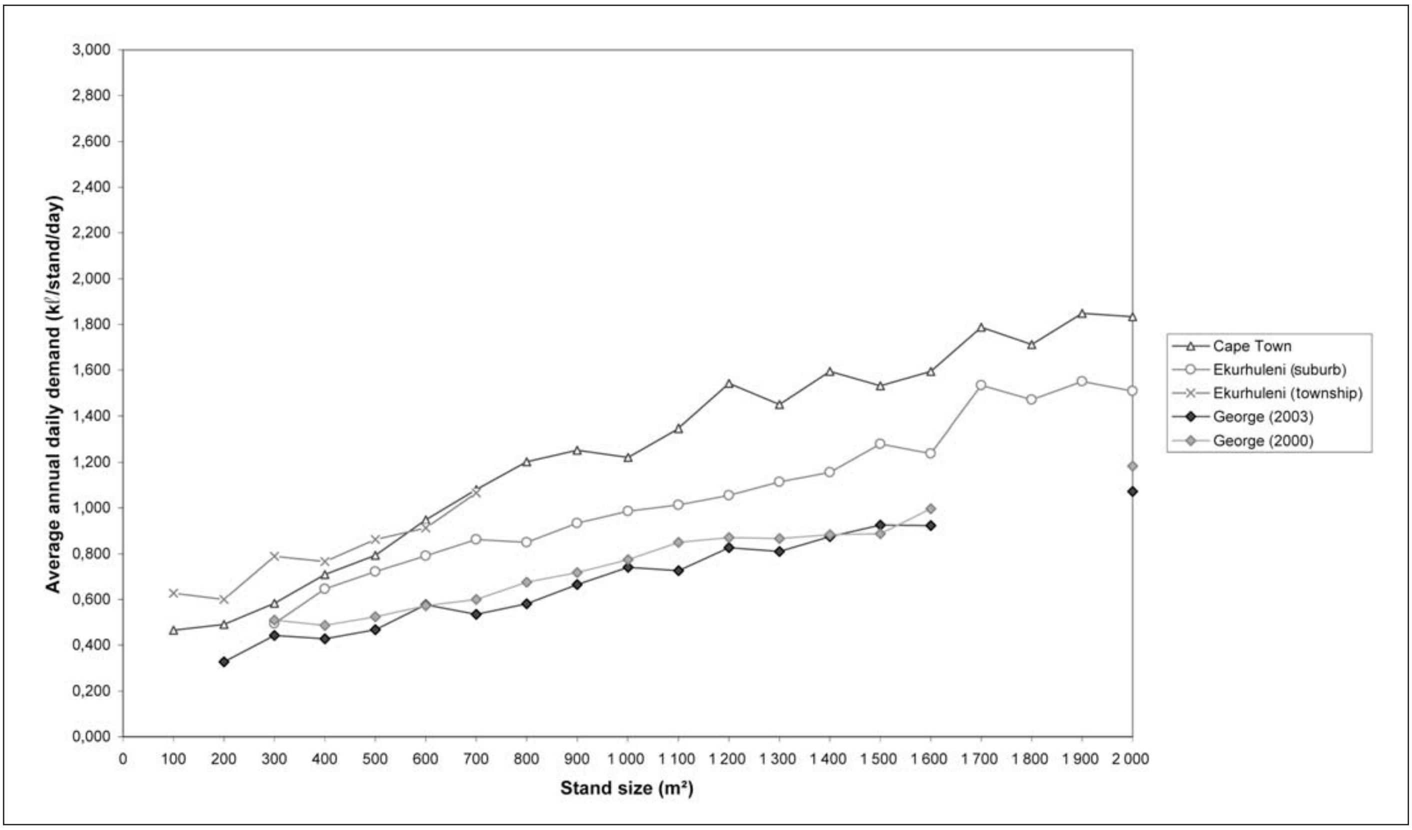
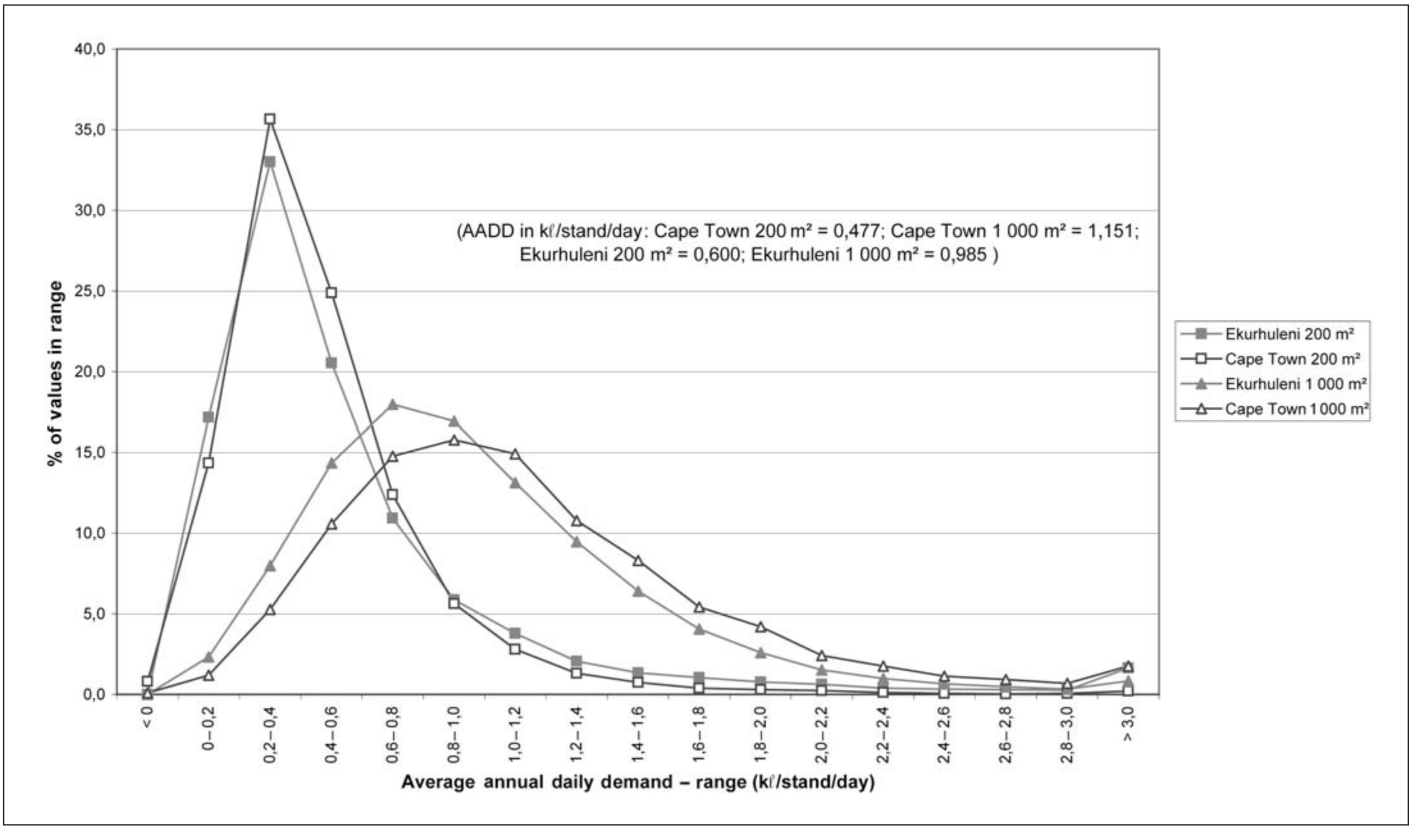


Figure 2 Results of water demand analyses for combined databases



(AADD in kℓ/stand/day: Cape Town 200 m² = 0,477; Cape Town 1 000 m² = 1,151; Ekurhuleni 200 m² = 0,600; Ekurhuleni 1 000 m² = 0,985)

Figure 3 Frequency histogram of water demand for two size classes

2. It is noted that insufficient data points are available for stand size range 1 650 $m^2 \leq A < 1\,950\ m^2$ for George and these points were not included in figure 2. Curves fitted to the data are presented later in this paper.

Geographic variation

The results clearly indicate that the AADD for a similarly sized stand in Cape Town is higher than for Ekurhuleni (suburbs), of which the AADD is higher than for George. For stand sizes smaller than 600 m² the difference is not significant. This variation in demand for different geographic regions is considered to be caused mainly by outdoor

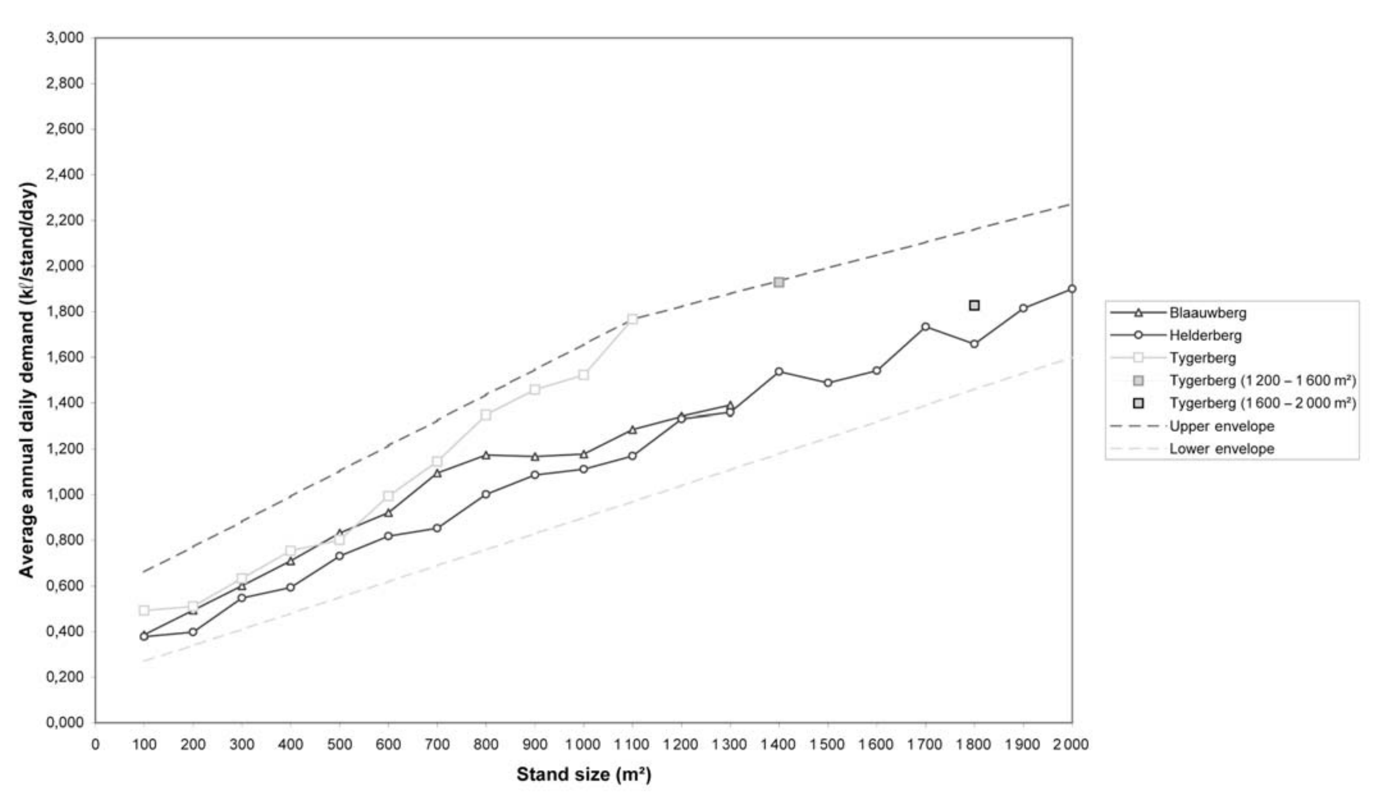


Figure 4 Results of water demand analyses for individual databases in Cape Town

use that is driven by the weather variables unique to each region. A slight reduction in the slope is noted for larger stand sizes; one explanation is that a relatively larger portion of larger stands are not cultivated or irrigated.

Suburban versus township stands

Townships in Ekurhuleni have a higher water demand than suburbs for the overlapping stand sizes between 300 m^2 and 700 m^2. Reasons for this may include the following:

- Household size (the number of people per household). It has been shown that the household size is positively correlated to water demand (Danielson 1979); the household size on a township stand could be expected to exceed that of a typical suburban stand (Rand Water 2001).
- Education regarding effective use of water is better rooted in suburban areas than in townships.
- It is possible that some township stand owners act as water vendors to nearby stands without adequate water supply.
- It is also common in urban areas that township home owners allow families to put up shacks on their stands and pay a monthly rent. These families are supplied with water and other services by the home owner. Such records could be included in the analysis (if the land use were recorded incorrectly by the treasurer as single residential). This would lead to an increased water demand for similarly sized township stands when compared to those in suburbs.
- Non-payment may be more prevalent amongst township consumers than those in suburbs, leading to an increased water demand in townships.

Stand size frequency distribution

A striking similarity is noted when the frequency histograms of water demand for a specific stand size class in two geographic regions are compared. Figure 3 illustrates the histograms for AADD pertaining to stands in two size classes as an example. The histogram of each size class has a unique shape; the corresponding distributions of the smaller stands will have a larger kurtosis and be more positively skewed than those of larger stands. The spread of data for larger stands is considered to be ascribed mainly to the larger portion of outdoor demand, which is more variable than indoor demand.

Individual databases

Similar categorisation of records per stand size class as shown in table 2 on page 4 for the combined datasets was conducted for all the individual databases. The subsets of the Cape Town and Ekurhuleni databases were also analysed individually. This enabled the researchers to compare the spread of data within each of the combined datasets in order to construct envelope curves. The mathematical descriptions of the guideline and envelope curves are presented later in this paper.

Cape Town

The individual results for Blaauwberg, Helderberg and Tygerberg (West, Central and South) are shown in figure 4. The three individual results have the same trend as the result presented in figure 2. The most critical point in view of an upper boundary of the envelope curve is that of Tygerberg, stand size 1 100 m^2. The Tygerberg 1 100 m^2 size class includes 416 records with an estimated error of 0,096 kℓ/day, or only 5,4 % of the mean. Stand size classes for stands in Tygerberg larger than 1 100 m^2 contained insufficient records to provide accurate results. Two additional stand size classes were included for sizes 1 200–1 600 m^2 and 1 600–2 000 m^2 to ensure that these possibly critical values were not discarded. The two points are also plotted in figure 4.

Ekurhuleni (suburbs)

The results for seven individual towns, based on the composition of treasury databases at the time of data extraction, were analysed. The results follow a clear trend and are scattered closely along the line for Ekurhuleni suburbs presented in figure 2. Scrutiny of the data showed that Bedfordview had to be separated from the remaining records because the stands in this area showed an exceptionally high water demand and were limited to stand sizes 1 700 m^2 and greater. These high water demands typify the exceptionally affluent single residential stands in the area. Knowledge pertaining to this type of consumer would have been lost if Bedfordview had not been separated from the other

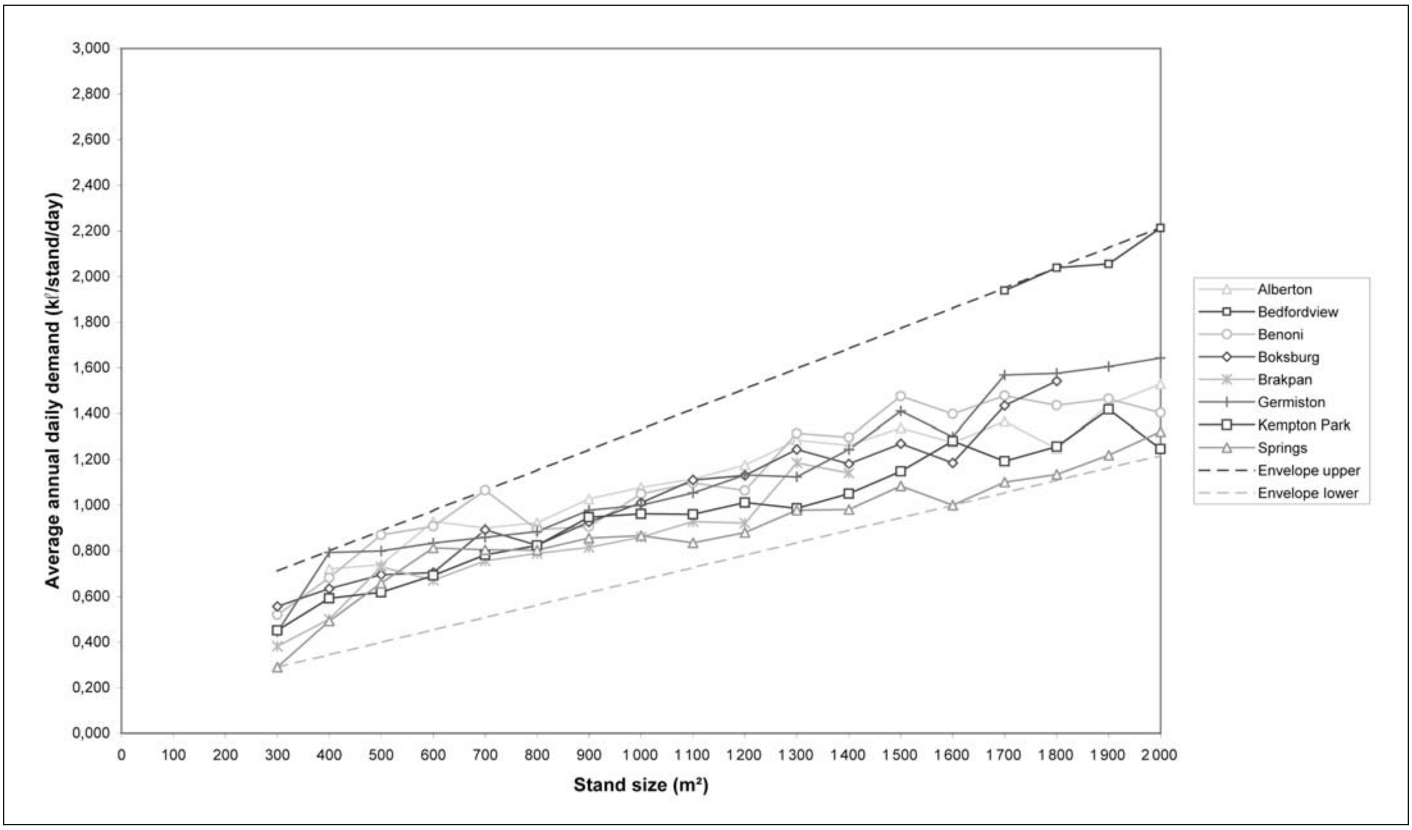


Figure 5 Results of water demand analyses for individual databases in Ekurhuleni (suburbs)

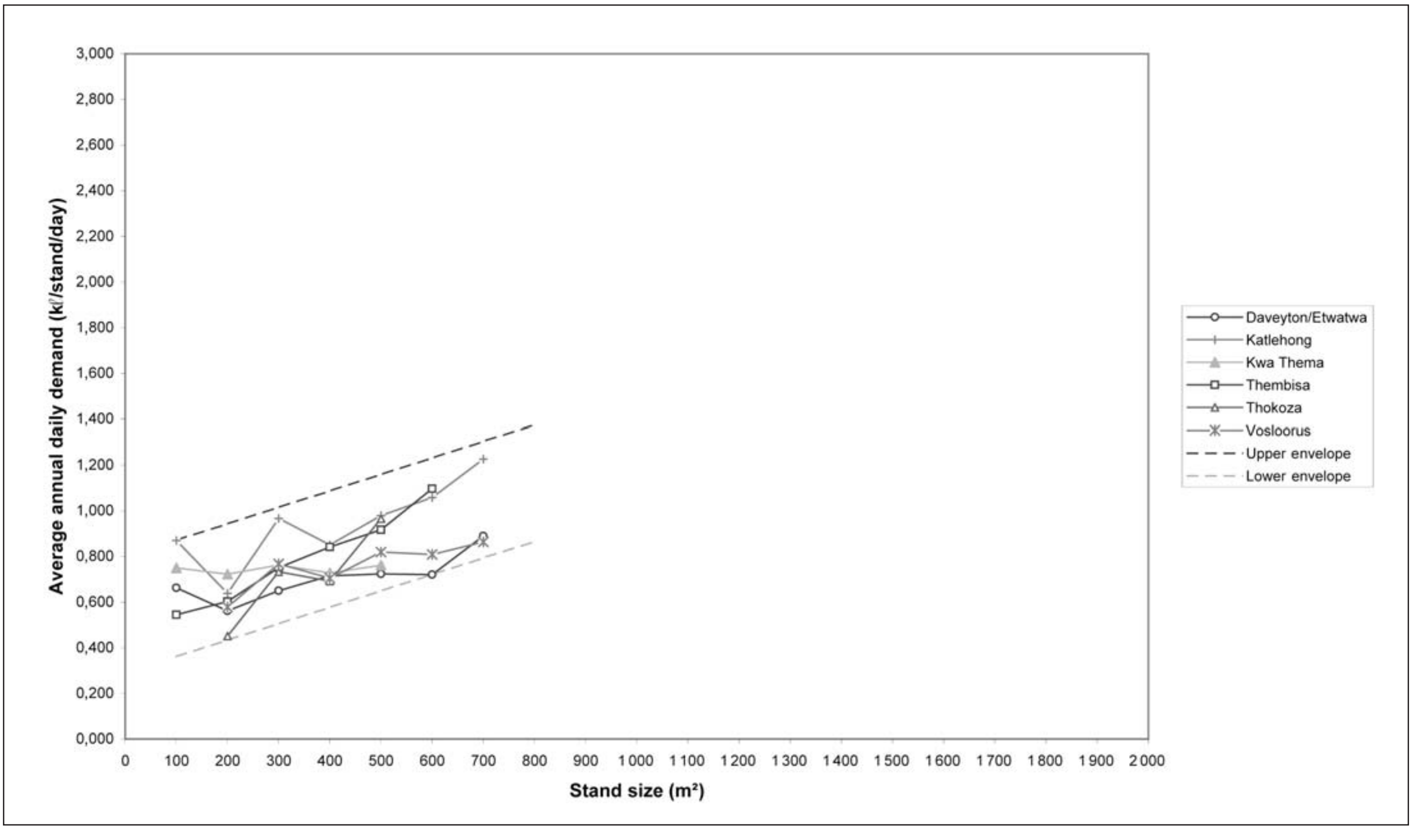


Figure 6 Results of water demand analyses for individual databases in Ekurhuleni (townships)

towns' data. All the size classes in Bedfordview fortunately included enough records to ensure an error of only 7,8 % for the mean of the most critical point, which was used to construct the upper boundary of the envelope curve.

The results of the eight towns, including Bedfordview as a separate entity, are shown in figure 5.

Ekurhuleni (townships)

Six of the treasury databases included records for townships. The results of the individual database analysis for the township stands are

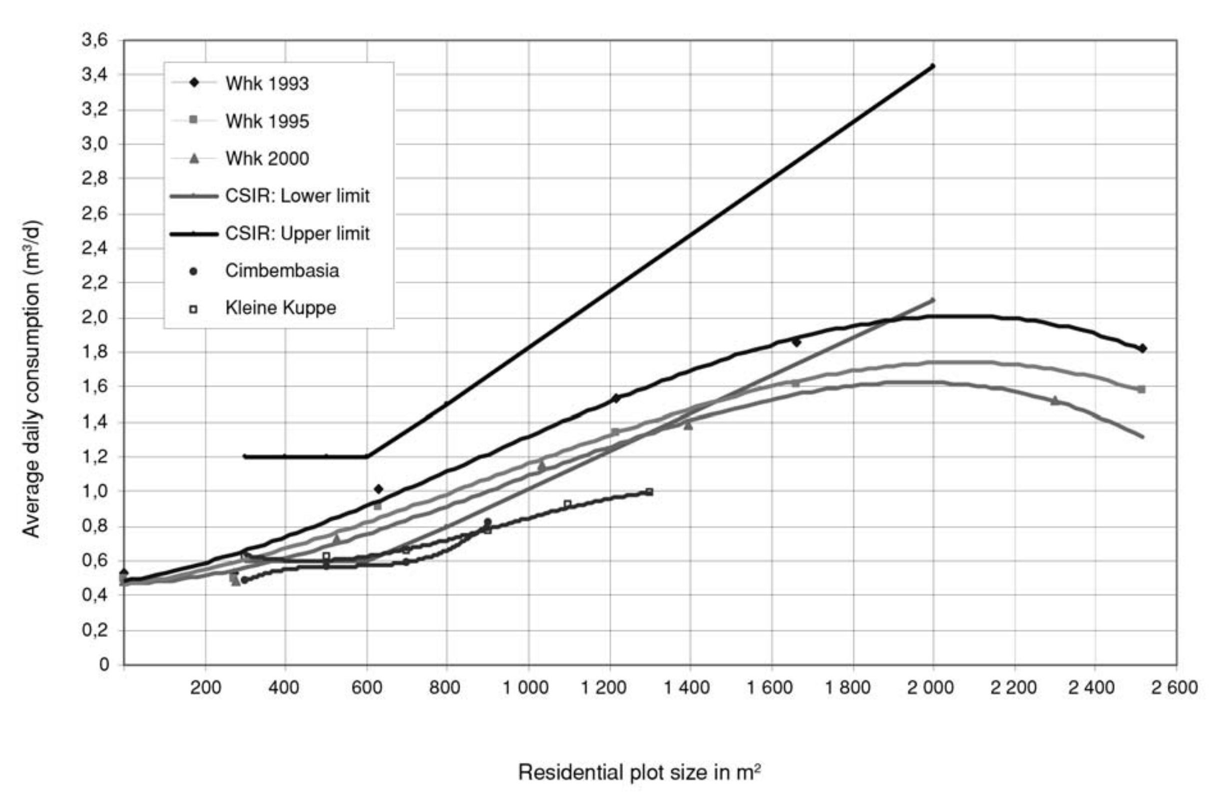


Figure 7 Average daily water consumption for residential plots in Windhoek

shown in figure 6. The spread around the values calculated from the combined database (refer to fig 2) is larger than for suburbs, but all follow the same trend as for the combined database.

DISCUSSION

Direct comparison of results with other work

CSIR guidelines

Comparison of figure 1 and figure 2 indicates that the two guidelines agree to a certain extent for the smallest stand sizes presented in the older guideline (between 400 m^2 and 600 m^2), but the CSIR guidelines are very conservative when compared to the presented results. The fact that the results indicate little change in demand for the smaller stand sizes over the years can be ascribed to the large contribution of indoor water demand to the total. The larger stands typically have larger irrigated gardens and thus a larger portion of outdoor demand. It has been shown that outdoor demand is significantly more price elastic than indoor demand (Howe & Linaweaver 1967) implying that outdoor water demand will reduce more than indoor demand when subjected to a price increase.

Stephenson and Turner (1996)

Work by Stephenson and Tuner (1996) on water demand patterns in Gauteng provides valuable insight into water demand. The work does not focus specifically on the relationship between AADD and stand size, yet such results are presented (refer to fig 1). As part of their work ten residential areas were selected and the water supply to each zone was measured by means of bulk meters. The relationship between the average stand size in the selected zone and the average AADD for that zone is presented in the article. The results based on the above method cannot be compared directly with the results in this investigation, because the guidelines presented in this paper focus exclusively on single residential stands and exclude UAW.

It can be expected that the AADD presented by Stephenson and Turner will be higher than found in this investigation due to the fact that some non-residential (possibly large) water use and unaccounted for water (leaks, municipal use, fire use, et cetera) in the supply system could be included in the zonal measurements. The use of average stand size for all stands in each zone can lead to a misrepresentation of stand size. Stephenson and Turner note that some of the zones included stands with more than one dwelling per stand and stands without individual water connections.

Despite the above discrepancies between the two studies, seven of the ten points provided by Stephenson and Turner fall within the envelopes presented in this paper. The other three points all fall close to the upper envelope of the CSIR guideline (refer to fig 1). Stephenson and Turner note that one of these points represents Alexandria and note that the study area was unusually densely populated, but provide no specific information regarding the other two points.

Windhoek water demand studies (Water Transfer Consultants 2001; WCE et al *2003)*

A model for water demand forecasting in Windhoek was developed using a time-series analysis. Independent variables identified were land usage, seasonal and deviant weather patterns, end-use water costs, drought reactions and water demand management initiatives.

The graph presented in figure 7 was compiled using the average consumption of residential properties in various suburbs (sample sizes of 20 % to 50 % of the residential consumers in each case). The results are based on the actual water consumption taken over specific calender years from the treasury system of the City of Windhoek. The data was analysed by evaluating individual reading dates and meter readings. Through the weather normalised consumption in the results it was estimated that the residential consumption could increase or decrease on average by 7 % to 9 % from the normalised consumption during hot dry periods or wet cool periods respectively. This was considered to be mainly a result of garden water use. In low-income areas (mainly water use inside the house) the weather influences were negligible. The lower water consumption in new townships (Cimbembasia and Kleine Kuppe middle-income areas) was considered to be the result of natural conservation through water demand management initiatives.

The AADD values per stand size from the Windhoek study follow the same trend as the findings from this investigation for

Table 3 AADD Reduction corresponding to a 50% stand size reduction

Description	Stand size (m^2)		% Reduction in AADD	
	Before reduction	After reduction	Jacobs *et al* (2003)	Van Zyl *et al* (2003)
Cape Town	2 000	1 000	35,8	–
Cape Town	400	200	31,1	–
Ekurhuleni suburb	2 000	1 000	37,3	28–40
Ekurhuleni suburb	1 000	500	29,7	
Ekurhuleni township	400	200	17,9	About 12
Ekurhuleni township	200	100	10,9	

Ekurhuleni and Cape Town, in that they are less conservative than the CSIR's Red Book guideline and have a flatter slope than the latter.

Jacobs and Haarhoff (2002)

Jacobs and Haarhoff (2002) applied an end-use approach to model residential water demand. They used the model to illustrate that the water demand for a residential stand can be expected to be higher in Cape Town than in Johannesburg and Durban. For irrigated lawn areas of 100 m^2 and 1 000 m^2 the demand for an identical stand in Cape Town was shown to be 8 % and 18 % respectively higher than one in Irene (Gauteng), and 10 % and 44 % respectively higher in Irene than in Durban. The work was based on monthly calculations and the assumption that the garden water demand is equal to the plant's ideal water requirements.

The findings from the end-use approach agree with the actual values from the analyses in this paper. The AADD values for the 18 overlapping stand size classes for Cape Town stands are on average 20 % higher than those in Ekurhuleni (suburbs), with a minimum of 6 % and a maximum of 30 % higher for each individual size class.

This investigation shows that the AADD for the 15 overlapping stand size classes is on average 39 % higher in Ekurhuleni (suburbs) than in George, with a minimum of 12 % and a maximum of 61 %. It appears that the relatively high annually sustained rainfall, low evaporation, and consequent lower potential evapo-transpiration in George and Durban lead to a lower AADD for similar sized stands in both George and Durban than in Gauteng.

Van Zyl et al *(2003)*

Van Zyl *et al* (2003) investigated the price, income, pressure, and stand size elasticity for stands in Alberton. Their work was conducted on a subset of the stands in Ekurhuleni used for analysis in this study. It should be kept in mind that elasticity varies along the demand curve for linear demand functions. However, in the definition used by Van Zyl *et al* (2003) the elasticity remains constant and a good fit can be achieved. Stephenson (1999) provides a more detailed explanation on elasticity and demand functions. It should be noted that the definition by Van Zyl *et al* for a suburb and township stand was based on valuations included in the treasury data and does not agree precisely with the definition used in this investigation.

The reduction in AADD for a change in stand size was calculated to compare findings from this work with that by Van Zyl *et al*. The guideline equations presented later in this paper were used to calculate AADD reductions for a few 50 % stand size reduction examples. The results are summarised in table 3. The table also includes the results presented by Van Zyl *et al* for the corresponding regions and stand types. In view of the fact that two different types of demand models were used the results compare very well.

Other Gauteng areas (2003)

Similar analyses to those for Cape Town and Ekurhuleni were conducted on 205 421 single residential stands from the Tshwane Metropolitan Municipality's treasury databases, with the exception that four stand size classes were applied in the Tshwane analyses to cover 500 m^2 each. Twenty-one results were obtained for six individual towns with sufficient records in each class to ensure a relatively small error. The results are presented in figure 8. The AADD is plotted against the average stand size for all records in the corresponding stand size class and town. No distinction was made in the Tshwane analyses between suburbs and townships.

It is clear that the Tshwane data tends towards the upper boundary of the envelope curves obtained from the Ekurhuleni analyses, especially for the Centurion, Pretoria and Akasia datasets. This could be expected

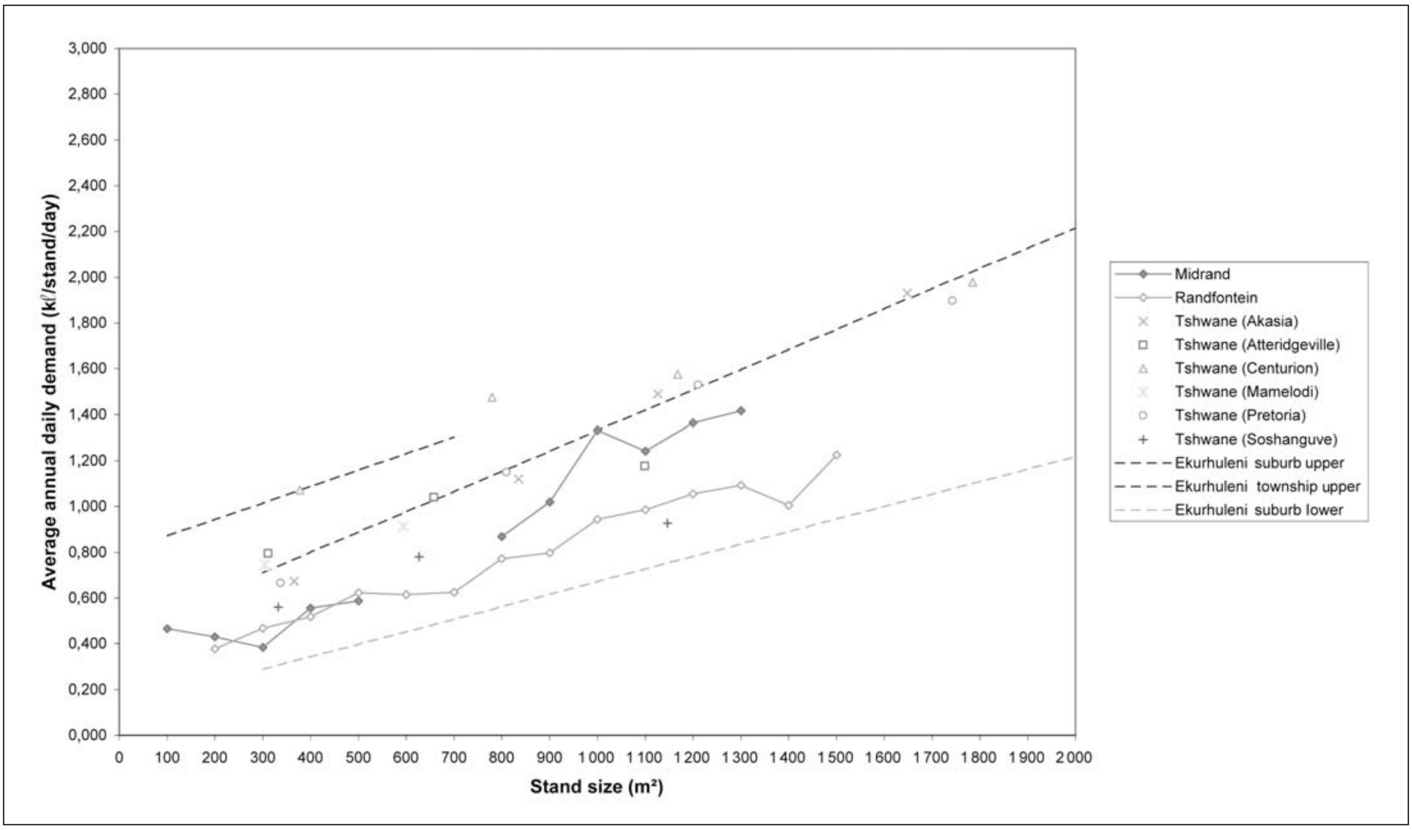


Figure 8 Results of water demand analyses for other Gauteng areas

since the latter areas could be considered to fall in a relatively high bracket with respect to affluency.

The AADD for Centurion at 780 m^2 stand size slightly exceeds the upper boundary of the envelopes for Ekurhuleni townships and suburbs. Subsequent analysis of the Centurion records showed that this point represents mainly stands in Laudium, which represents a concentration of consumers with a relatively higher socio-economic profile located on smaller sized stands. This illustrates the effects of socio-economic profile on AADD. A single coefficient model such as the one presented in this paper does not explain such effects.

With the exception of the single result discussed above, the other 20 sets of values obtained from the Tshwane analyses agree well with the results presented in this paper for Ekurhuleni.

The same procedure that was used for the analyses of the Cape Town, Ekurhuleni and George data was applied to obtain results for Midrand and Randfontein with 8 257 and 13 570 single residential records respectively. Some results in Midrand were discarded due to a lack of sufficient records in some stand size classes. These results are also plotted in figure 8 and can be seen to fall within the envelope curves for Ekurhuleni.

Limitations

Supply from other water sources

Garlipp (1979) recognised that alternative water sources are used at some stands in conjunction with municipal supply. Even though this cannot be ignored, such stands are not identified in the treasury data or the SG's data and could not be excluded from the analysis. The most common alternative sources are ground water from boreholes, rainwater from roofs, and on-site re-use of grey water. The most common application of these alternative sources is probably garden irrigation, which could explain some of the variation in demand for the larger stands. Until further work is conducted on the application of alternative on-site water sources it can only be assumed that current trends of such water use will persist.

Single coefficient model

In constructing this single coefficient model the effects of other parameters influencing water demand were not directly addressed. The most significant are probably water price, socio-economic profile of consumers, household size, and weather variables such as rainfall and evaporation. The envelopes presented in this paper are included to allow for such influences.

Apart from stand size, this guideline also attempts to respect some of these parameters:

- The guideline curves for three geographical regions partly respect the influence of weather on demand.
- The influence of the household size, as well as income, is partly accounted for by presenting townships and suburbs as unique stand types.
- In order to reduce the effect of price changes on the results the selection of treasury records was limited to span a relatively small time period of less than three years. The results for different time periods in George and Windhoek indicate that the change in demand over such a relatively small time span is not necessarily significant.

Weather parameters

The weather parameters during the time of measurement in Ekurhuleni and Cape Town had to be compared with the long-term average to ensure that the measured water demand was not subject to significant influences by abnormal weather.

Weather statistics were obtained from the South African Weather Service and included monthly rainfall and evaporation for the weather stations at Alberton (0476196), Cape Town International Airport (0021179/8) and Johannesburg International Airport (0476399/8); the numbers in brackets represent the rainfall station numbers. The periods of record are 1970, 1959 and 1958 to date respectively, with the exception of evaporation where all measurements ceased in 1988. Monthly temperature values for station 0476399/8 were also obtained.

In the case of Johannesburg it was possible to approximate the annual evaporation for later years by means of linear regression to temperature and rainfall for the purpose of comparing to the long-term average. For Cape Town additional information could be obtained for two weather stations at Elsenburg (1972 to date) and Nietvoorbij (1967 to date).

The mean annual precipitation (MAP) over the entire record period at each station is: 684 mm/year (Alberton 0476196), 531 mm/year (Cape Town 0021178/9), and 724 mm/year (Johannesburg 0476398/9). The actual mean annual evaporation (MAE) over the measured period of record for the two stations is: 1 879 mm/year (Cape Town 0021178/9), and 2 162 mm/year (Johannesburg 0476398/9). The MAE in Johannesburg is 15 % higher than in Cape Town, but the MAP is 36 % higher.

Findings from the analyses of weather statistics for the Ekurhuleni study period, 2001 to 2002, include:

- Johannesburg MAP was only 3 % higher for 2001–2002 than the long-term average (740 mm/yr versus 724 mm/yr).
- Alberton MAP was 9 % lower for 2001–2002 than the average (627 mm/yr versus 684 mm/yr).
- The estimated evaporation for 2001–2002 was slightly lower than the measured average up to 1988 (2 132 mm/yr versus 2 162 mm/yr).
- The average daily temperature was almost the same for 2001–2002 as the average (15,8 °C versus 16,0 °C) and the maximum daily temperature was the same in 2001–2002 as the average (22,0 °C versus 22,0 °C).

Analysis of statistics for the three years corresponding to the three Cape Town database record periods, 1999–2002 (excluding 2001), led to the following findings:

- Cape Town MAP was 16 % lower for the record period than the long-term average (447 mm/yr versus 531 mm/yr).
- The average MAE at Nietvoorbij for 1999-2002 was 12 % lower than the average for the record period (1 664 mm/yr versus 1 844 mm/yr) and at Elsenburg it was 9 % lower (1 818 mm/yr versus 1 956 mm/yr).

Theoretically the lower-than-average MAP at Cape Town during the study period could have led to higher than average water demand for garden irrigation, but in contrast the lower evaporation would have reduced the required demand for garden watering. It can be concluded that the results from this investigation are not based on abnormal weather conditions as compared to recorded statistics at Cape Town and Johannesburg over the 44-year record period.

GUIDELINE FOR RESIDENTIAL DEMAND ESTIMATION

The construction of three guideline curves and corresponding envelope curves are discussed separately for three geographic regions and two stand types. When stand size is available as the sole explanatory variable these curves will provide a more accurate water demand estimate than those previously published. In each case the mathematical demand function as well as the resulting curves are provided for practical application.

If it is assumed that Cape Town, Ekurhuleni and George represent the coastal winter rainfall region, inland summer rainfall region, and coastal annual rainfall region of the country respectively, the following guidelines for demand estimation can be constructed.

Coastal winter rainfall region

Guideline curve – coastal winter rainfall region

The guideline curve for the coastal winter rainfall region is based on the data presented in figure 2 for Cape Town. Statistical analysis of the data indicates that two linear equations, with separate slopes, best fit the data – instead of a single linear fit. The change in slope could be partly explained by considering the fact that no distinction could be made between townships and suburbs in the datasets for Cape Town, as discussed earlier in this paper. However, from the Ekurhuleni data where townships and suburbs could be separated, it was found that the water demand of township stands in the overlapping stand size range (300 m^2 to 800 m^2) is higher than for suburban stands of the same size. For Cape Town,

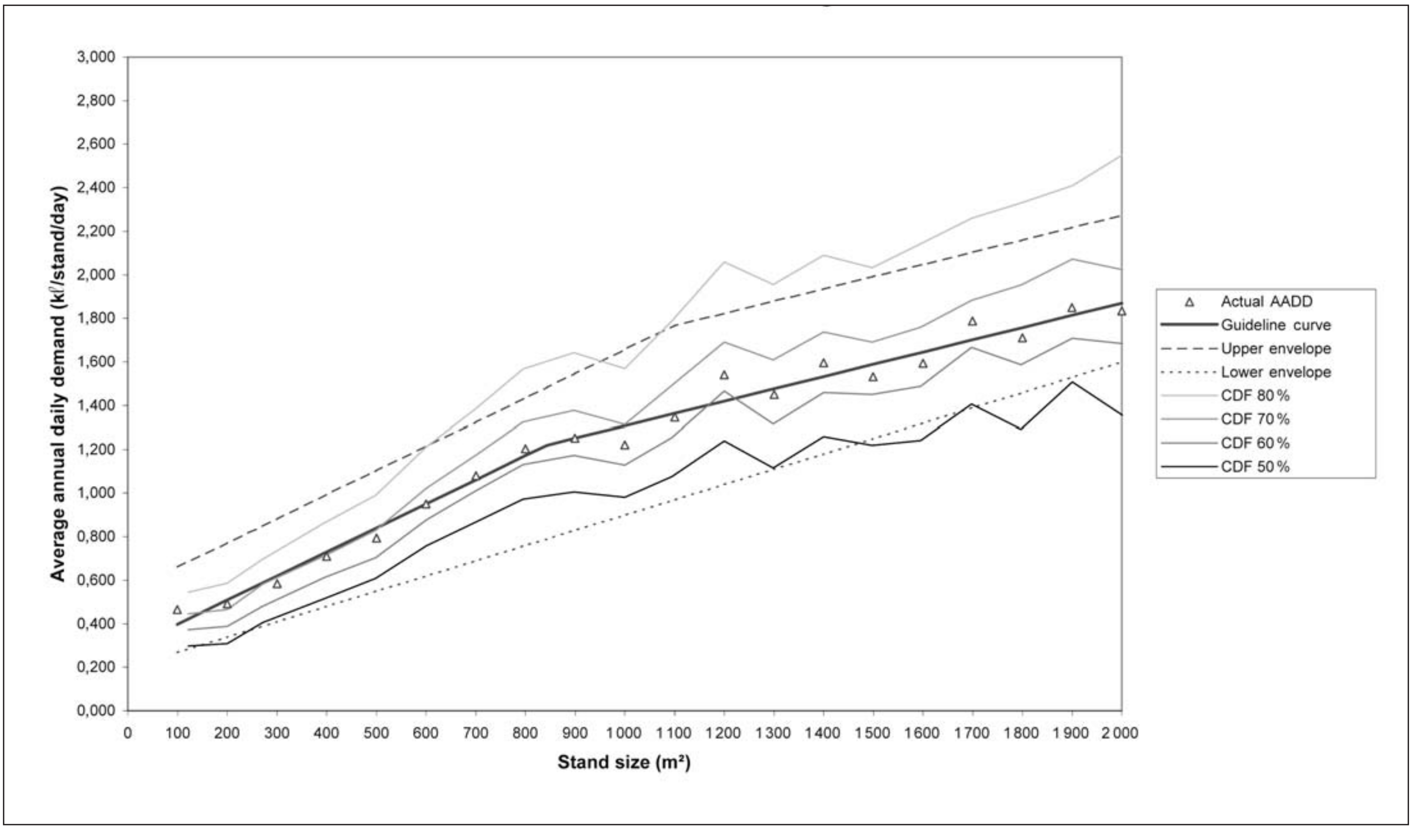


Figure 9 Guideline for water demand estimation of a single residential stand – coastal winter rainfall region

where township-type and suburb-type stands are combined in one dataset, a different slope could be expected above and below a stand size of approximately 800 m^2.

Two equations were calculated based on the least squares method for stand sizes 100 m^2 to 800 m^2 and 800 m^2 to 2 000 m^2. The R^2 values of 0,981 and 0,928 respectively for the correlation between the linear equations and the data points are relatively high (a single linear fit was also constructed, but was discarded in favour of the former method, mainly due to the linear curve being less conservative for AADD estimates between stand sizes of 600 m^2 and 1 200 m^2).

In order to construct a practical mathematical model over the entire stand range the intersection of the curves was calculated. The mathematical form of the guideline curve presented in figure 9 is:

$$Q_W = \begin{bmatrix} (0{,}00110595)\cdot A + 0{,}287 & (50\,m^2 \le A < 840\,m^2) \\ (0{,}00056253)\cdot A + 0{,}745 & (840\,m^2 \le A < 2\,050\,m^2) \end{bmatrix} \qquad (1)$$

where Q = average annual water demand (kℓ/stand/day)
A = single residential stand size (m^2)
and subscript W denotes the coastal winter rainfall region

Envelope curves – coastal winter rainfall region

The upper boundary of the envelope is more critical than the lower and was also split into two sections. The same two slopes as in equation 1 were used, but the two equations were constructed to intersect the highest point of all the individual databases – that for Tygerberg at 1 100 m^2 with an AADD of 1,767 (refer to fig 4).

The lower envelope follows the slope of the linear trend through the combined Cape Town data, but the intersect of the linear equation was moved down by visual inspection to originate just below the lowest point. The mathematical description of the envelope curve is:

$$HIGH_W = \begin{bmatrix} (0{,}00110595)\cdot A + 0{,}551 & (50\,m^2 \le A < 1\,100\,m^2) \\ (0{,}00056253)\cdot A + 1{,}148 & (1\,100\,m^2 \le A < 2\,050\,m^2) \end{bmatrix} \qquad (2)$$

$$Q\_LOW_W = [(0{,}0007000)\cdot A + 0{,}200 \quad (50\,m^2 \le A < 2\,050\,m^2)] \qquad (3)$$

where Q_HIGH = Upper boundary of the envelope of average annual water demand (kℓ/stand/day)
Q_LOW = Lower envelope of average annual water demand (kℓ/stand/day)
A = Single residential stand size (m^2)
and subscript W denotes the coastal winter rainfall region

Inland summer rainfall region (suburbs)

Guideline curve – inland summer rainfall region (suburbs)

The linear least squares fit to the data for Ekurhuleni (suburbs) presented in figure 2 has a high R^2 value of 0,968, indicating a good fit to the data. The guideline for suburban stands in the inland summer rainfall region is based on this analysis and is presented in figure 10 and equation 4:

$$Q_S = [(0{,}00058)\cdot A + 0{,}395 \quad (250\,m^2 \le A < 2\,050\,m^2)] \qquad (4)$$

where Q = Average annual water demand for suburban stand (kℓ/stand/day)
A = Single residential suburban stand size (m^2)
and subscript S denotes suburban stand type in the inland summer rainfall region

Envelope curves – inland summer rainfall region (suburbs)

The upper and lower linear envelope curves were constructed through the two points resulting in the highest curve position and lowest position respectively, based on the individual database results. The points used for the highest curve are 700 m^2 stands in Benoni and 1 800 m^2 stands in Bedfordview. The lowest curve intersects the results for Springs' 300 m^2 and 1 600 m^2 stands (refer to fig 5).

The mathematical description of the envelope curve is:

$$Q\_HIGH_S = [(0{,}0008845)\cdot A + 0{,}447 \quad (250\,m^2 \le A < 2\,050\,m^2)] \qquad (5)$$

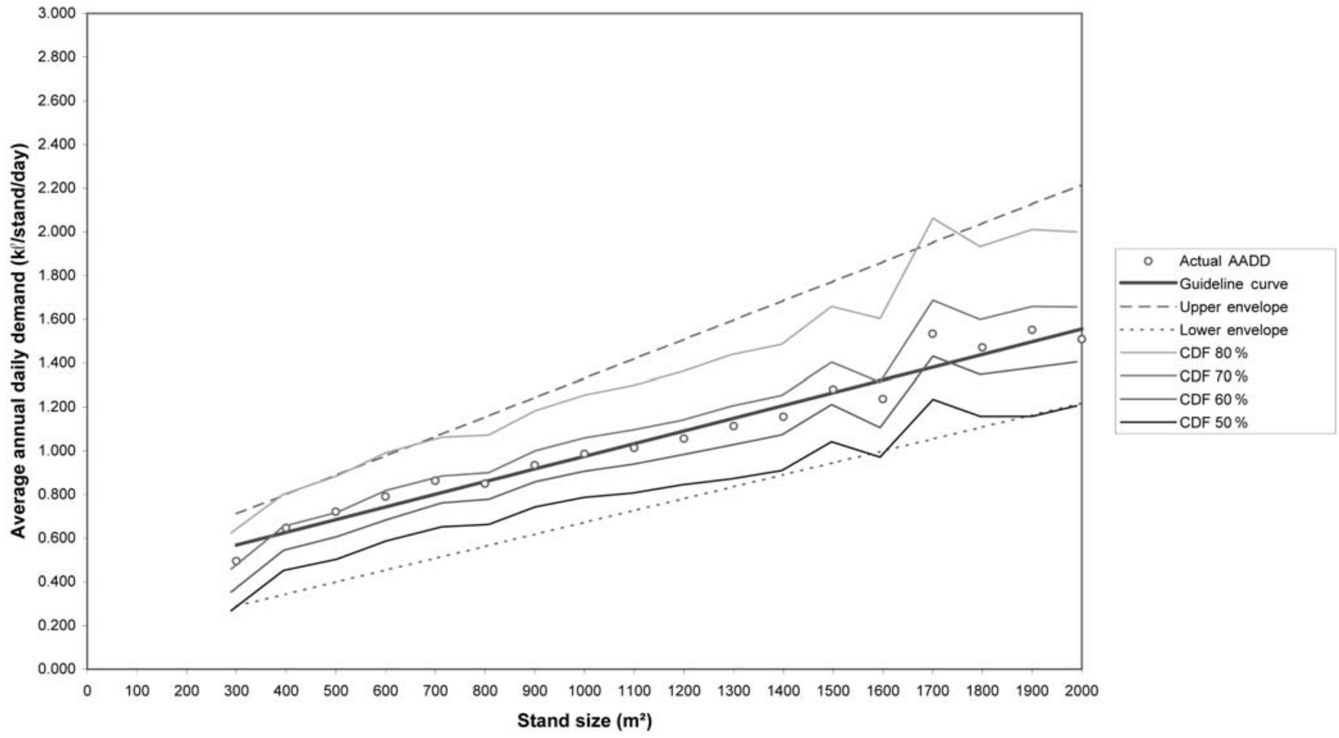


Figure 10 Guideline for residential water demand estimation inland – summer rainfall region (suburbs)

$Q\_LOW_S = [(0{,}0007000) \cdot A + 0{,}200 \quad (250\ m^2 \leq A < 2\ 050\ m^2)]$ (6)

where Q_HIGH = upper boundary of the envelope of average annual water demand (kℓ/stand/ day)
Q_LOW = lower envelope of average annual water demand (kl/stand/day)
A = single residential suburban stand size (m^2)
and subscript S denotes suburban stand type in the inland summer rainfall region

Inland summer rainfall region (townships)

Guideline curve – inland summer rainfall region (townships)

The same procedure was followed for construction of a guideline curve as for the inland summer rainfall region (suburbs), but the combined dataset for townships was used to conduct the linear least squares fit. The R^2 value for the fit is 0,916 indicating a good fit to the data. The model for township stands in the inland summer rainfall region is presented in figure 11 and equation 7.

$Q_T = [(0{,}0007) \cdot A + 0{,}515 \quad (50\ \text{m}^2 \leq A < 750\ \text{m}^2)]$ (7)

where Q = average annual water demand for township stand (kℓ /stand/day)
A = single residential township stand size (m^2)
and subscript T denotes township stand type in the inland summer rainfall region

Envelope curves – inland summer rainfall region (townships)

In view of the larger spread of data around the guideline it was decided to construct a linear envelope curve by using the same slope as the guideline curve. The upper and lower envelope curves were formed by the equations that intersect the highest and lowest points of the individual database results (refer to fig 6). The upper boundary of the envelope intersects the result for 100 m^2 stands in Katlehong, and the lower envelope intersects the Daveyton-Etwatwa result for 600 m^2 stands.

The mathematical description of the envelope curve for township stands in the inland summer rainfall region is:

$Q\_HIGH_T = [(0{,}00072) \cdot A + 0{,}800 \quad (50\ m^2 \leq \text{A} < 750\ m^2)]$ (8)

$Q\_LOW_T = [(0{,}00072) \cdot A + 0{,}290 \quad (50\ m^2 \leq \text{A} < 750\ m^2)]$ (9)

where Q_HIGH = upper boundary of the envelope of average annual water demand (kℓ/ stand/day)
Q_LOW = lower envelope of average annual water demand (kℓ/stand/day)
A = single residential township stand size (m^2)
and subscript T denotes township stand type in the inland summer rainfall region

Coastal annual rainfall region (George)

Guideline curve – coastal annual rainfall region

The results for George (year 2003) were used to conduct a linear least squares fit and construct a guideline curve for coastal regions with an annual sustained rainfall. The R^2 value for the fit is 0,978 indicating a good fit to the data. The guideline equation for the coastal annual rainfall region is presented in equation 10

$Q_A = [(0{,}0004132) \cdot A + 0{,}282 \quad (50\ m^2 \leq \text{A} < 2\ 150\ m^2)]$ (10)

where Q = average annual water demand for suburban stand (kℓstand/day)
A = single residential stand size (m^2)
and subscript A denotes coastal annual rainfall region

RELIABILITY BOUNDS

The large number of data points also enabled the researchers to construct reliability bounds for the data. Kolmogorov-Smirnov tests indicated that the data within stand size classes are not normally or lognormally distributed. It was subsequently decided to apply nonparametric statistics to construct a cumulative distribution function (CDF) for each of the combined databases' stand size classes. The 50 %, 60 %, 70 % and 80 % CDF are superimposed onto the guideline

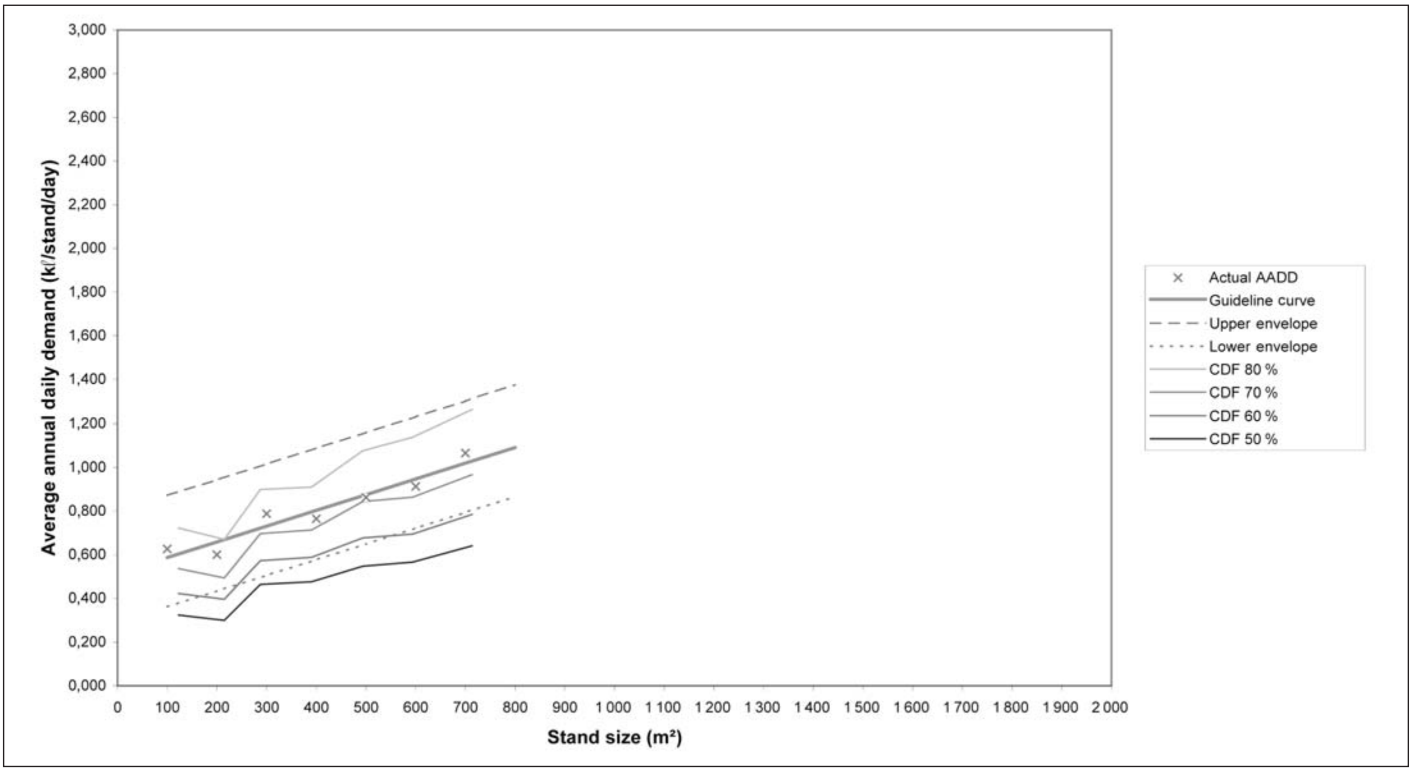


Figure 11 Guideline for residential water demand estimation – inland summer rainfall region (townships)

and envelope curves presented in figures 9, 10 and 11 for each of the geographic regions.

The upper boundary of the envelope curves correspond approximately to the 80 % bound of the CDF, and the lower envelope curves to the 50 % bound.

CONCLUSION

A strong relationship exists between the AADD and stand size. However, estimates of single residential AADD and subsequent analyses of water demand and water supply systems should preferably be based on measured data for the area under investigation. The AADD is normally extended to calculate peak water demand and sewer flow for the preliminary design of water supply and sewer systems. The AADD eventually impacts an authority's water and sewer infrastructure budget and finally its expenditure. Current guidelines are too conservative, leading to unnecessary expenditure. In the absence of measured data, guideline curves presented in this paper should be used to estimate AADD for single residential stands.

The estimates obtained in this manner are for residential water demand. Estimates of UAW should be added in order to design water infrastructure.

Although numerous factors influence demand the stand size is used in this model as a single explanatory variable. Unique models for three geographic regions as well as envelope curves are presented to respect the influence of other variables. The socio-economic profile of consumers appears to influence demand significantly within each region. The average AADD of stands in exceptionally affluent suburbs follow the upper boundary of the envelope while in less affluent suburbs it follows the lower envelope.

The guideline curve presented in this paper for each region can be used to estimate the AADD unless a specific reason exists to apply the lower or upper boundary of the envelope instead. The AADD in the Tshwane area should be estimated by applying the upper boundary of the envelope for the inland summer region rather than the guideline curve. It should also be noted that Windhoek has a stringent water demand management program in place.

It is proposed that the results presented in this paper form the base for estimating residential water demand in future. The results could replace old guidelines, which are more conservative.

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