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Effect of stand size and income on residential water demand

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This study investigated the independent effects of stand size and stand value (as a surrogate for income) on residential water demand. The study was based on the measured AADD (annual average water demand) of approximately 195 000 domestic users in the Tshwane and Ekurhuleni metropolitan areas. To remove the interdependencies between stand size and value, the data was divided into categories with similar stand sizes and values. The data was analysed in two parts: the first to investigate AADD; and the second to investigate water demand elasticity. The study found that AADD increases with both increasing stand size and stand value, and that the current design guidelines overestimate the AADD for large stands. These results confirm the work by previous researchers such as Van Vuuren and Van Beek (1997) and Jacobs *et al* (2004). A new envelope for the minimum and maximum AADD as a function of stand size is proposed. The data did not show strong elasticity trends, but it was found that the typical values for the stand size elasticity vary between 0 and 0,5, and for the stand value elasticity between 0 and 0,6.

INTRODUCTION

Annual average daily demand (AADD) is a crucial parameter in the design and analysis of water distribution systems. The capacities of service reservoirs, elevated storage tanks, pumps, and bulk and distribution pipes are determined mainly by the projected demand requirements of an area. These demand estimates are, in turn, based on design guidelines or measured data for similar supply areas.

The document *Guidelines for human settlement planning and design* (CSIR 2000), commonly known as the Red Book, is normally used in South Africa to estimate AADD. The AADD of developed residential areas is determined from a figure giving upper and lower limits for the demand as a function of stand size. To determine the appropriate AADD for a given stand size within this range, the designer has to take other factors into consideration. Various factors besides stand size influence water demand in developed areas, including climate, income, water price, pressure, population density, use of water-saving devices and regulatory factors such as water restrictions.

While most of these factors are independent of each other, this is not the case for income and stand size. More affluent areas often have larger stand sizes, although the movement towards housing complexes opposes this trend. That income and stand size are not independent of each other creates difficulties when water demand is modelled, for example to determine the projected average demand for a new area or to study the effect of changes in water consumption through an end use investigation.

The aim of this study was to investigate the independent effects of both stand size and stand value (stand value includes the value of the stand and improvements, and is used as a surrogate for income) on water demand. The study was based on the measured AADD of approximately 195 000 domestic users in the Tshwane and Ekurhuleni metropolitan areas. To remove the correlation between stand size and stand value, the data was separated into categories of similar stand sizes and stand values. The independent effect of stand size on demand was then investigated in each stand value category. Similarly, the independent effect of stand value on demand was investigated in each stand size category.

The data was analysed in two parts: the first to investigate AADD; and the second to investigate water demand elasticity. The basic data analysis is discussed first, followed by the AADD, and then the demand elasticity investigations.

DATA ANALYSIS

Water consumption data for the study was obtained from the Swift software package, which is used by both Tshwane and Ekurhuleni metropolitan municipalities. Swift is a commercial software package that interrogates municipal treasury databases and enables the user to analyse recorded water consumption. It gives access to information on individual users, of which the stand size, value of site, value of improvements, suburb, water demand, land use and zoning were extracted for use in this study. Swift includes monthly water consumption

Table 1 Stand size and value categories

| Category no | Stand size (m ²) | Stand value (R) |
|-------------|------------------------------|-----------------|
| 1 | 200–260 | 50 000–65 000 |
| 2 | 260–300 | 65 000–85 000 |
| 3 | 300–380 | 85 000–130 000 |
| 4 | 380–760 | 130 000–170 000 |
| 5 | 760–1 000 | 170 000–200 000 |
| 6 | 1 000–1 400 | 200 000–245 000 |

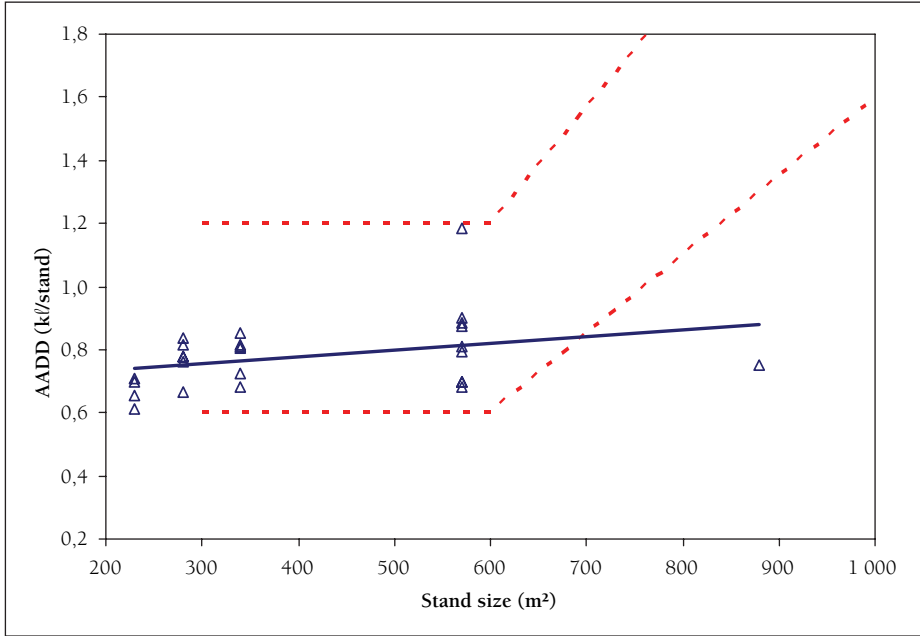


Figure 1 AADD vs stand size for the R65 000 to R85 000 stand value category. The Red Book guideline range is also shown

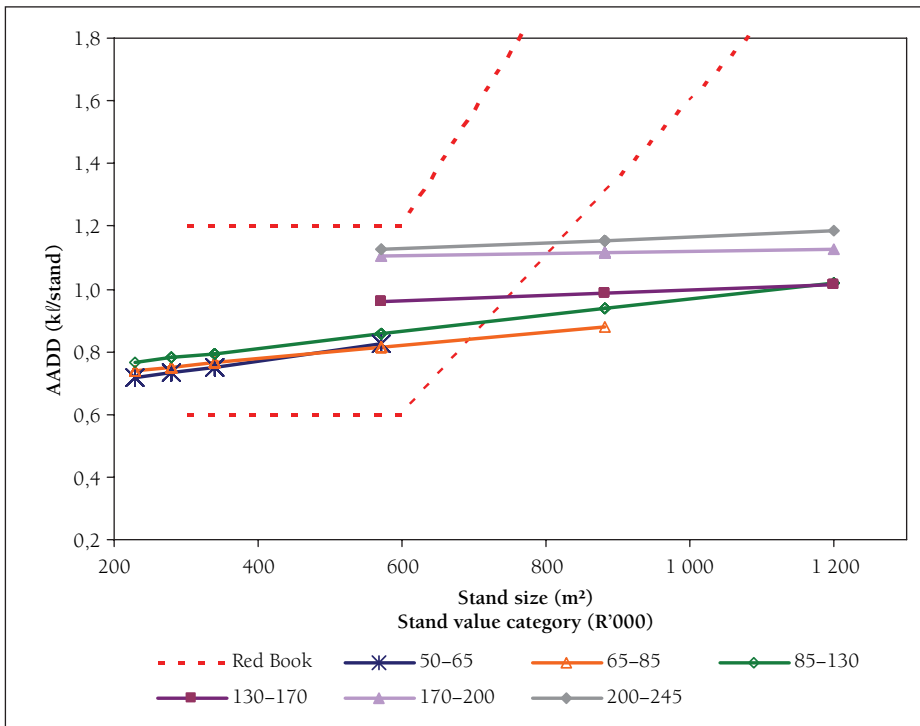


Figure 2 AADD as a function of stand size for different stand value categories

per stand and uses data for the previous 12 months to calculate the average annual daily demand. These values are based on monthly water meter readings and thus exclude losses in the water distribution network.

Records for 769 393 users, including at least 12 months of consumption data,

were extracted for the following cities: Alberton, Atteridgeville, Benoni, Boksburg, Brakpan, Centurion, Edenvale, Kempton Park, Mamelodi, northern Pretoria, Pretoria and Springs (Husselmann 2004). The data was filtered to exclude erroneous and unrealistic data points, as well as users falling

outside the limits set for the study. There are many reasons for incomplete or wrong treasury information, including unmetered users, vacant stands, broken water meters, users not included in the treasury system, or no data available for the stand size or stand value. The study was limited to residential users with stand sizes between 200 and 1 400 m², and stand values between R50 000 and R245 000. Users with an average daily consumption of less than 0,01 kl/day or more than 10 kl/day were also excluded in order to focus on typical residential water demand rather than extreme cases. To be included, a data point had to pass all the filters, which significantly restricted the amount of data. Only 64 %, 30 % and 61 % of the data passed the individual stand size, stand value and demand filters respectively. The vast majority of stands that were filtered out did not have stand values or had stand values less than R50 000. After filtering, 195 000 (25 %) records remained for analysis.

An attempt was made to link income data directly to the database using the 2003 national census data. However, census income data could only be obtained on a suburb level and was thus not suitable for a study based on individual users. It was decided to base the study on the stand value (the sum of the municipal valuations of the value of the stand itself and improvements) as a surrogate for income. It was felt that stand value gives a good indication of income. It is also an internationally accepted practice to use stand value as a surrogate for income (Dandy *et al* 1997). Municipal stand valuations have not been updated to reflect the current market values, but are assigned on a reasonably consistent basis. It was thus assumed that the municipal valuations provide a good representation of stand values relative to each other.

To remove the interdependence between stand size and value, the data for each city was separated into six stand size and six stand value categories. The category boundaries (see table 1) were selected on the full data set to ensure that each category had roughly equal numbers of records. However, the distribution of records for most cities showed more data points in certain categories, reflecting local demographics. The average parameter (stand size or value) and AADD were calculated for each category. Only results for categories representing more than 3 % of the data points in a city were used to analyse the effect of stand size and value on water demand.

ANNUAL AVERAGE DAILY DEMAND

To investigate the effects of the stand size on AADD, the AADD was plotted against stand size for each stand value category and city. Since the stand values in each category are

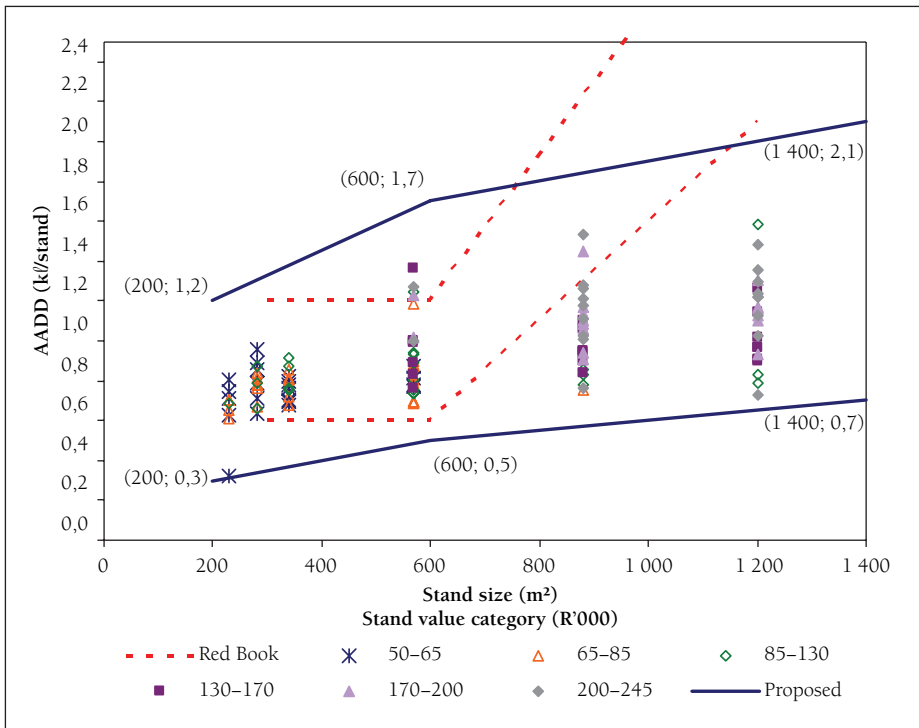


Figure 3 Proposed new design envelope for AADD showing data points and the current design envelope

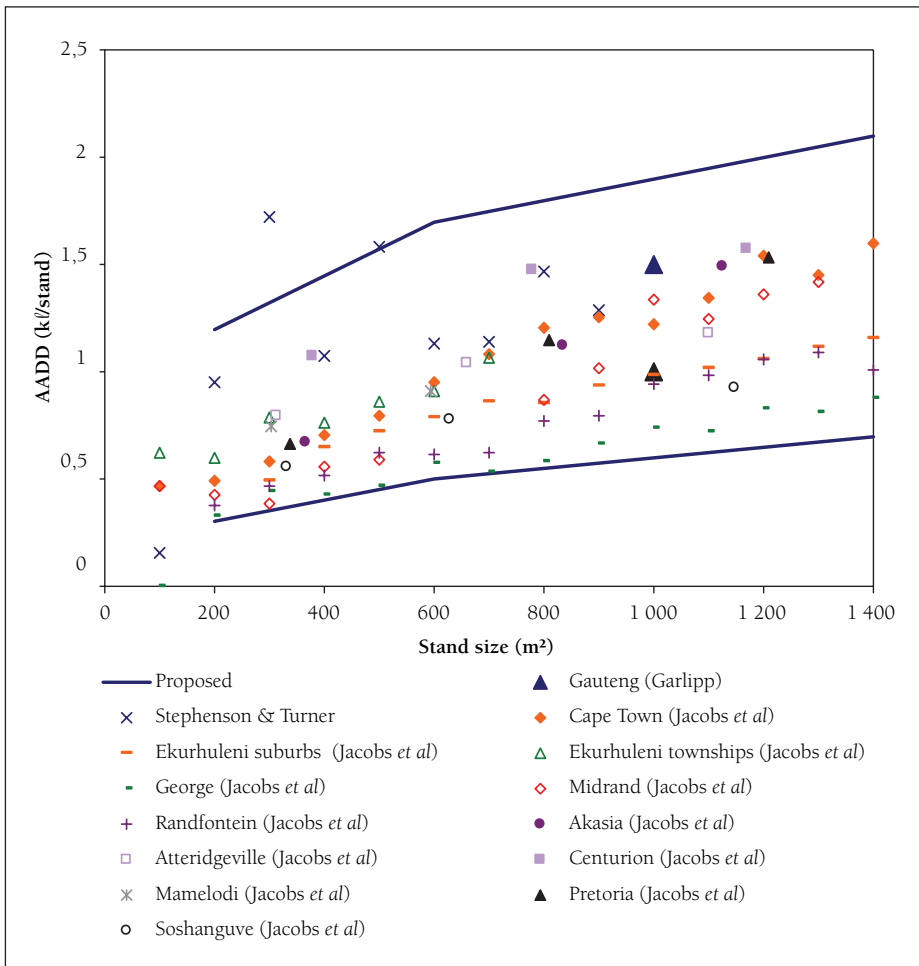


Figure 4 Proposed new design envelope for AADD showing the results of previous studies

similar, the graphs represent the effect of stand size without the effect of stand value. A linear trend line was fitted to the data. A typical graph is shown in figure 1 for the R65 000 to R85 000 stand value category.

The trend lines for each of the six stand value categories were then plotted on the

same axes as shown in figure 2. The Red Book minimum and maximum guideline values are also shown. Figure 2 shows a clear relationship between AADD and stand size for all stand value categories, with AADD increasing with increasing stand size. The higher the stand value, the greater

the AADD for the same stand size. This relationship can also be shown by plotting AADD against stand value for the stand size categories. However, stand value is a subjective measure, likely to vary between municipal areas and with time. It is thus believed that stand size is a better indicator of the demand envelope, with stand value (or income) playing a part in determining the relative position of a given supply area between the upper and lower bounds. It is proposed that income should be used as one of the many factors that will determine the relative position of the design AADD within the proposed envelope.

It can also be noted from the figure that the higher the stand value, the smaller is the slope of the AADD vs stand size trend line. Finally, it is clear that while the AADD values for smaller stands fall within the Red Book guideline values, the Red book overestimates the AADD for larger stands. For stands larger than 800 m², the trend lines fall below even the minimum envelope line proposed by the Red Book. The observation that the Red Book guideline values overestimate the AADD for large stand sizes is not new, but has been pointed out by authors such as Van Vuuren and Van Beek (1997) and Jacobs *et al* (2004).

To provide a better estimate of AADD, all the data points on which the lines in figure 2 are based were plotted on a graph showing the Red Book guideline values (see figure 3). The demand-area relationship seem to flatten for larger stand sizes, which is in contrast with the trend implied by the Red Book envelope curves. This is probably due to higher intensity irrigation occurring in small stands compared to larger stands (which will have a greater fraction of non-irrigated area).

New design envelope curves are proposed in figure 3 based on the results of the analysis. A conservative approach was followed by choosing the upper envelope line higher than all the data points. The lower envelope line was chosen to be close to the data points. While straight lines and an inflection point at a stand size of 600 m² are used in the proposed envelope, there is no reason that the proposed curves should not consist of curved lines. However, more investigation is required to provide an accurate estimate of the shape of these lines.

The proposed minimum AADD limit is lower than that of the Red Book for all stand sizes. The proposed maximum AADD curve exceeds that of the Red Book for stand sizes below approximately 750 m² and is lower for the rest. Significantly, its maximum line is lower than even the minimum Red Book line for stand sizes exceeding 1 150 m². This represents a substantial reduction in design AADD for larger stands and will have a marked impact on the cost

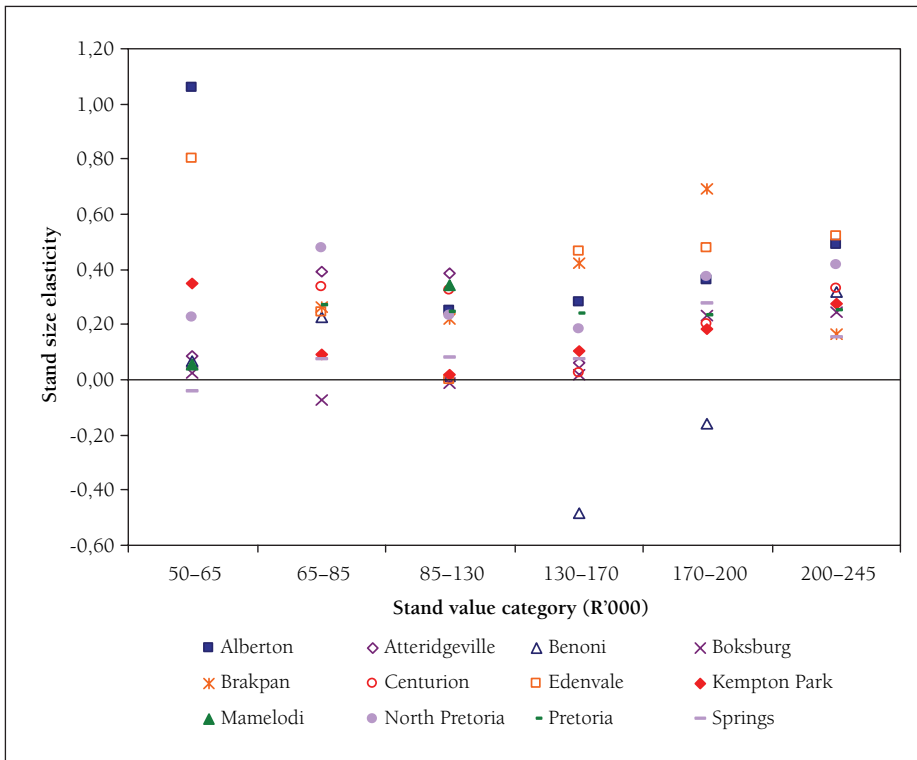


Figure 5 Stand size elasticities

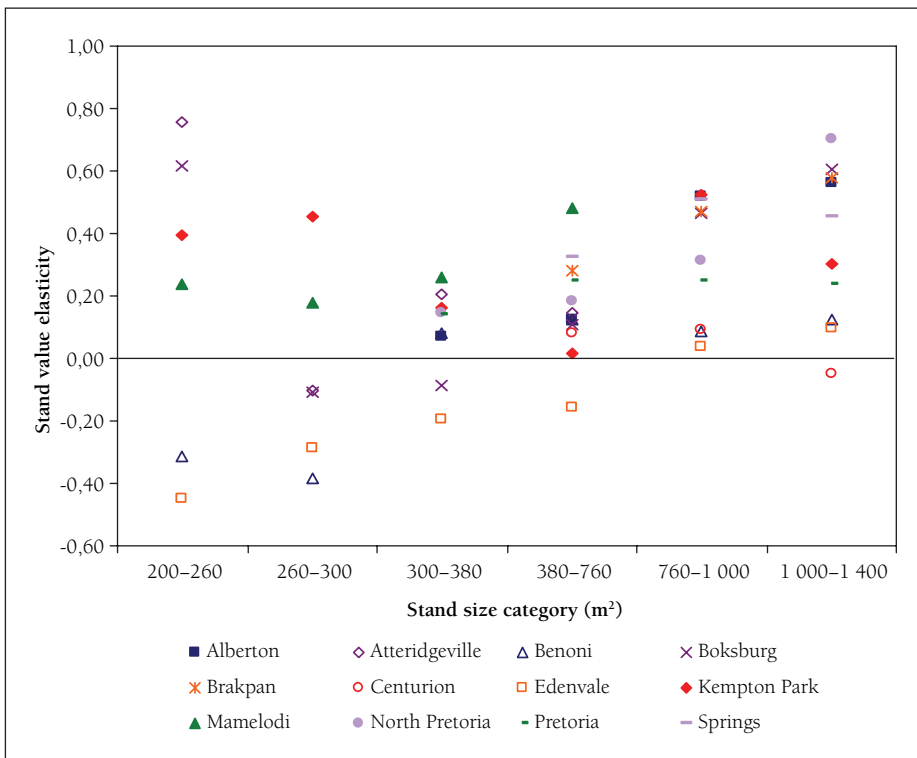


Figure 6 Stand value elasticities

of providing water supply infrastructure to these areas.

To test the proposed AADD envelope it was compared to a number of previous studies published by Garlipp (1979), Stephenson and Turner (1996), Van Vuuren and Van Beek (1997) and Jacobs *et al* (2004) as shown in figure 4. Most data points fall inside the proposed envelope. The exceptions are two values reported by Stephenson and Turner on the higher side, and some values for George on the lower side. The values of Stephenson and Turner include losses

in the AADD values, which is the likely reason for the high AADD values of these two points. George presents a special case owing to its coastal setting, its popularity as a tourism destination and the rainfall throughout the year. The envelope in figure 3 is proposed as a general guideline. Jacobs *et al* propose demand curves for specific regions and climates, and cover a much larger stand size range than this study. However, in the stand size range covered by this paper, the curves proposed by Jacobs *et al* generally fall within in the envelope curve in figure 3.

ELASTICITY

Elasticity is defined as the sensitivity of a parameter such as water demand to a given factor. Elasticities are used to model the effect of various possible scenarios on the water demand in an area. Various studies have been done on the elasticity of water demand with respect to the price of water (Gibbs 1977, Howe 1967, Van Zyl *et al* 2003, Veck & Bill 2000, Agrhe 1986, Young 1973), income (Cameron & Wright 1990), stand size (Van Zyl *et al* 2003), pressure (Lebaka, 2003 & McKenzie 2001), climate (Kulk 1993) and the number of people per household (Morgan 1975). Relatively little is known about the elasticity values for stand size and value. This study aimed to provide some elasticity values for these parameters based on the data analysed.

Although elasticity can be defined in various ways (Van Zyl *et al* 2003), the definition used in this study is given by:

$$D_2/D_1 = (F_2/F_1)^\beta \quad (1)$$

Where D is water demand, F a factor affecting water demand, and β is the elasticity. The subscripts 1 and 2 denote the value of the variables before and after a change respectively.

To obtain elasticity values, the data was analysed for each stand size and stand value category in each city. To reduce scatter, the data in each category and city was further grouped into 5 % intervals, thus producing 20 data points. Power curves were fitted to these data points to determine the elasticities. Because many categories were used, large variations occur in the number of data points used to calculate elasticities. This, combined with the unpredictability of water demand behaviour on a small scale, means that the elasticities found can at best be used as a general guide and should not be seen as exact values.

The elasticities of water demand with respect to stand size are shown in figure 5 for the different stand value categories. The figure shows a range of stand size elasticities mainly between 0 and 0,5 for middle and large stand sizes. The R50 000 to R 65 000 stand value category has a larger spread of stand size elasticity values with Alberton and Edenvale having elasticities above 0,8.

A few negative elasticity values are evident from the figure. A negative elasticity means that the water demand will decrease with increasing stand size and is not likely. However, most of the negative values are near the zero line and the fact that they are negative is probably not significant in relation to the accuracy of the estimate. On the whole, it can be concluded that the vast majority of elasticities fall between 0 and 0,5. There is little evidence of a trend in the elasticity values with increasing stand value (or income).

The elasticities of water demand with respect to stand value are shown in figure 6 for different stand size categories. The figure shows more scatter than the stand size elasticity graph, especially in the smallest and largest stand size categories. More negative values are also evident, especially in the lower stand size categories. Negative stand value elasticity implies that users with higher stand value (and thus income) will use less water than users with lower stand values for the same stand size. One possible explanation for this behaviour is the trend in high-income families towards townhouse or cluster units where houses and paved areas are typically larger, and gardens thus smaller than the same size stands of lower value.

On the whole, most elasticities fall between 0 and 0,6, with negative elasticities (down to a value of -0,4) occurring in the smaller stand size categories.

CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to investigate the independent effects of both stand size and income (stand value was used as a surrogate for income) on water demand. The study was based on the measured AADD of approximately 195 000 domestic users in the Tshwane and Ekurhuleni metropolitan areas. The data was sorted into categories of similar stand sizes and stand values to be able to study the two factors independently of each other. The properties of the AADD and water demand elasticities were investigated.

The study found that there is a definite trend of increasing water demand with increases in both stand size and stand value. It was concluded that stand size is a good measure for defining an AADD range. The design engineer should use information such as income, climate, level of living to determine an appropriate AADD within the minimum and maximum range. It was shown that increasing stand value increases the AADD, but also reduces the slope of the curve.

A comparison of the results with the proposed Red Book (CSIR 2000) guidelines for water demand showed that the Red Book

guideline can underestimate the AADD for small stand sizes, and overestimate the AADD for stand sizes larger than approximately 700 m². A new envelope curve for estimating AADD is proposed (figure 3) based on the data analysed. The curve was tested against the findings of previous studies on AADD and proved to work well.

The proposed AADD curve has large implications for the design of distribution network and bulk supply pipes, municipal storage reservoirs, elevated storage and pumping capacity in the system, especially for larger stand sizes. Substantial savings in the cost of water supply infrastructure as well as improvements in water quality through reduced retention times can result if this guideline is implemented. However, it is important to note that the guideline AADD values do not include losses in the water distribution system, which often represent a substantial proportion of a municipality's average water consumption. Using more accurate values for the AADD increases the importance of using realistic peak factors and leakage values in design.

The elasticity analysis found a relatively large spread of values for the various cities and categories. Most stand size elasticities fall between 0 and 0,5, but no strong trends of the elasticities with stand size could be identified. Most stand value elasticities fall between 0 and 0,6, with some negative elasticities occurring in the smaller stand size categories. The elasticity results add to the limited published data on elasticities for stand size and stand value (or income).

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