Application of a residential end-use model for estimating cold and hot water demand, wastewater flow and salinity

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Abstract

The structure and data requirements of an end-use model for residential water demand and return flow are presented in a companion paper. This paper focuses on the practical application of the model. The model is first applied to confirm a few commonly observed water demand patterns: Seasonal variation in demand, the positive correlation between average annual daily water demand and stand size, and the increase in water demand, hot water demand and wastewater flow with an increase in household size. The convergence between the predicted model results and independently observed values by others encourages practical use of the model. Secondly, the effects of some specific water demand management measures are evaluated by adjusting selected model parameters. The measures include xeriscaping, the installation of dual-flush toilets and low-flow showerheads, pool ownership and pool cover use. The model provides a rapid means to obtain first estimates of the likely effects of different water demand management measures.

Keywords: water consumption - mathematical models, water salinisation, hot water supply

Introduction

An end-use model for water demand and sewer flow analysis is discussed in a companion paper (Jacobs and Haarhoff, 2004).

In this paper the authors demonstrate the practical application of the model. Some definitions, abbreviations and acronyms used in the companion paper are not repeated here, as they are common to both papers.

The residential end-use model (REUM) enables the analyst to estimate the indoor- and outdoor water demand, hot water demand, wastewater flow, and concentration of total dissolved solids (TDS) in the wastewater flow for an individual residential stand and a given set of input parameters. This makes the model unique – although other end-use models have been developed, applied and studied in South Africa (Van Zyl et al., 2004) none combine these five components into one model.

In this paper REUM is verified by investigating the convergence between the predicted model results and independently observed values by others. The paper also illustrates how a few specific water demand management (WDM) measures could be evaluated in detail with the use of REUM.

Factors influencing the model results

Numerous factors influence the indoor and outdoor water demand, hot water demand, wastewater flow and salinity. In REUM provision is made for 79 parameters, each varying over 12 months, to completely describe these five components. Table 1 indicates those parameters that require adjustment in this present investigation. For a full list of model parameters, reference could be made to Jacobs and Haarhoff (2004). Some of these parameters are briefly discussed below.

Household size

The notation used to describe the so-called quantity parameter in REUM is n. The parameter n is equal to the household size for most indoor end-uses. For the purpose of this investigation the household size is considered to be measured in units of people per household (PPH). In other words, it is the number of water consumers on the stand.

Many values for household size have been published. The 51 published values that could be obtained from the literature vary between 2.6 and 4.7 PPH for suburbs, with a typical value of approximately 3.3 PPH for South African suburbs.

As could be expected, the value is higher (and less predictable) for township stands, ranging from 3.8 to 8.2 PPH for the seven published values obtained; no typical value is apparent. Up to 27 PPH have been reported (Simpson, 1983), but these higher values include more than one household, or tenants, on a single stand; such stands are not included in the present investigation.

It has been reported that *per capita* water use decreases substantially with an increase in the household size. The reduction in *per capita* water demand from 1 to 4 PPH, recorded in a detailed study by Edwards and Martin (1995), was about 40%. This value pertains almost exclusively to indoor demand, because the reported outdoor demand represents less than 5% of the total. Morgan (1973) presents similar findings regarding reduced *per capita* water demand with an increase in the household size.

However, for the illustration of **differences** due to different WDM measures in this paper (which cannot affect the household size) it was decided to maintain a constant *per capita* demand.

Blended water temperature

The desired "hot" water temperature is a blend of hot and cold water, thus it is termed blended water temperature. The value appears to be linked to the human body temperature (about 38°C). Relatively small variation around this value has been reported in

<table>

TABLE 1 Description of parameters investigated			
Aspect investigated	**Model adjustment required**		
	Description	**Parameter**	**REUM notation**
General characteristics			
All	Household size	Household size	d
Geographic Significance	Monthly rainfall	Rainfall	R
	Monthly pan evaporation	Evaporation	p
Hot water demand	Desired hot water temperature	Blended temperature	T_b
WDM measure or adjustment			
Toilet retrofit	Conventional toilet	Large flush volume	$b_{TOILET\ LARGE}$
	Dual flush toilet	Large flush volume	$b_{TOILET\ LARGE}$
	Dual flush toilet	Small flush volume	$b_{TOILET\ SMALL}$
Shower retrofit	Shower nozzle flow rate	Shower event volume	b_{SHOWER}
	Shower duration	Shower event volume	b_{SHOWER}
Pool	Pool evaporation	Pool cover use factor	$f_{POOL\ EVAPORATION}$
Leaks	Per capita leaks	Leak volume	b_{LEAKS}
Washing machine	Washing machine brand choice	Soluble substance mass	$t_{WASHING\ MACHINE}$
	Retrofit washing machine	Event volume	$b_{WASHING\ MACHINE}$
Xeriscaping	Vegetation type and crop factor	Crop factor	$k_{m,VEGETATION\ TYPE}$
	Vegetation surface area	Surface area	$s_{VEGETATION\ TYPE}$
	Garden Irrigation Factor	Garden irrigation factor	$f_{VEGETATION\ TYPE}$

</table>

literature and measured by the authors, limited to a tolerance of less than 4°C above or below 38°C.

Leaks

A discussion regarding water leaks in distribution systems, such as provided by McKenzie et al. (2002), is beyond the scope of this paper. So-called plumbing leaks, representing leaks on a stand downstream of the consumer's water meter, are termed "leaks" in this paper.

Lambert et al. (1999) suggests that a minimum night flow of 100 ℓ/stand·d is an average performance for a system with typical pressure and density of service connections. DeOreo et al. (1996) report 27.4 ℓ/c·d of leaks from a detailed study (i.e. 82.2 ℓ/stand·d for a household size of 3 PPH). The latter value is used in this investigation as an illustrative example to represent leaks.

Toilet flush volume

A dual-flush toilet has a large and small flush volume, instead of only one volume for a flush event. Various types of dual-flush toilets are available. Comparative tests between two models were conducted by DeOreo et al. (2001) as part of a retrofit programme. In South Africa dual-flush toilets are relatively expensive and are not readily available. Dual-flush toilets commonly use 6 and 3 ℓ/ flush, or 9 and 4.5 ℓ/flush, for large and small flushes respectively.

Some argue that dual-flush toilets need to be flushed twice to effectively clear the pan. However, DeOreo et al. (2001) found that double flushing was not a problem with the dual-flush toilets used in their retrofit programme (the entire toilet comprising cistern and pan needs replacement to ensure that an effective flush is maintained during dual-flush operation).

When modelling dual-flush toilets the flush frequency has to be analysed by considering flush frequency for each of the large and small flush types independently. Butler (1991) found that 58% of dual-flush toilet's flushes were small – for the purpose of this study a 60/40 ratio for small/large flush frequency of a dual-flush toilet is assumed.

The typical flush volume used in this investigation to model a conventional toilet is 14.3 ℓ/flush. For a dual-flush toilet 6 and 3 ℓ/ flush are used as illustration in this paper for the large and small flush respectively.

Shower event volume

The event volume for the shower is determined by the flow rate of the nozzle multiplied by the duration of the shower event. Numerous literature references and measurements indicate that a low flow head discharges about 0.1 ℓ/s while a high discharge would be about 0.3 ℓ/s (as high as 0.5 ℓ/s has been reported). Typical shower duration is 300 s, but this could vary significantly – normally between about 120 s and 820 s.

The above values suggest 12 ℓ/event and 246 ℓ/event as the minimum and maximum shower event volumes respectively. However, lower and higher values than these have been reported in the literature for extreme events. The most typical shower event volume is considered to be 60 ℓ/event.

Pool evaporation (pool cover use)

Pool evaporation is dependent mainly upon the pool water surface area and evaporation (in REUM pool filtering is calculated separately and is unaffected by the use of a pool cover). Pool water surface area was found to vary between 12m² and 60m², with an

average of 35 m² per pool. When investigating a single residence the exact pool surface area could be entered into the model, but in order to compare the REUM results to actual water consumption of a larger number of homogeneous stands it would be necessary to appropriately reduce the pool size based on the actual number of residences with pools.

It was found that 38% of all respondents during a survey indicated the presence of a pool (Rand Water, 1998). Taking into account this fraction an average pool surface area for all stands is 13,3m² per stand. The lack of information for other geographical regions led to the adoption of the value for other areas as well.

In the case of a pool the parameter *f* describes the efficiency of evaporation from the pool surface. Thus, no pool cover implies complete evaporation $(f_{POOL} = 1)$, whereas the use of a pool cover implies that no evaporation can take place $(f_{POOL} = 0)$.

For the purpose of this study a "pool cover" is defined as any device that completely covers the entire pool surface area so as to prevent water from evaporating from the pool surface. Pool covers merely aimed at the safety of toddlers (such as net-type covers) have no effect on evaporation and are ignored.

The brand of washing machine powder

The soluble substance mass added at each end-use is modelled in REUM. The washing machine was chosen for illustrative purpose in this investigation.

Patterson (1999) reports a significantly different mass of soluble salts for 40 different brands of washing powder analysed in Australia. It is reported in that study that up to 40% of some products' mass is merely soluble salts used as industrial fillers with no active role during the washing process.

A similarly wide spread of values is apparent for different South African products analysed by the authors. Six washing machine powders tested produce significantly different results for the total mass of soluble substances. The range is 29 870 mg to 88 430 mg per single dosage (i.e. per end-use event). The chosen value for modelling a baseline scenario is 60 000 mg per dosage and represents the typical value of washing machine detergent powders.

Human habits regarding the addition of soluble substances to the wastewater stream cannot easily be determined, unless it is known which brand names' product is used at the stand (this normally varies over time).

Vegetation type and crop factors

The different methods for measurement of climatological parameters pertaining to evaporation and the subsequent methods for estimating pan and crop factors were compared by Sentelhas and Folegatti (2003). They point out that the conversion factors vary depending on site and weather conditions. For the purpose of this investigation, values for these factors published in the WRSM90 Appendices (Midgley et al., 1994) for different regions of the country are used. However, crop factors for lawn grass genotypes are not included in their work.

The water demand and crop factors for numerous lawn grass genotypes were investigated by Short and Colmer (1999) in Perth, Australia. Of all the various genotypes studied, *Pennisetum glandestinum* (kikuyu) was considered to be most applicable for lawns in South Africa, and subsequently the crop factor value for kikuyu was used for modelling lawns in this study.

Only a mid-summer crop factor value for each genotype is presented by the above authors, leaving the monthly distribution of

the value unknown. In order to obtain such an estimate (12 monthly values are required as input to REUM) it was assumed that the crop factor for kikuyu is distributed monthly in the same manner as the crop factor for the vegetation type "Pure Grassveld", presented by Midgley et al. (1994). The latter authors also provide crop factors for various natural veld types – ones that could be used to estimate values for similar vegetation types in residential gardens.

Vegetation surface area

A parameter for stand size is not included directly in the structure of REUM. Instead, the irrigable areas of up to three different vegetation types have to be provided. In order to include the stand size as an independent variable in REUM it is thus necessary to obtain a relationship between total stand size and the irrigable area of the stand.

A cadastral stand layout superimposed on high resolution aerial photographs was used to estimate lawn sizes of a few stands in relation to the total stand size (such photos are available for many South African cities). A few additional stands were also physically inspected. Based on the analyses of 14 stands, the irrigable lawn size appears to vary between 20% and 30% of the total stand size in most cases, and the total irrigable (vegetated) garden area normally varies between 30% and 40% of the total. The smallest stand analysed had an area of 290 m² and the largest 1 944 m².

Only residential stands smaller than 2 000m² are considered in this paper. The main reason for this limitation includes the fact that – by far – most of the 600 000 residential stands analysed as part of work by Jacobs et al. (2004), which is used for comparison, are smaller than 2 000 m².

Aerial photographs and -inspections suggest that a typical low-income township stand has an insignificantly small vegetated area, if any. However, the stands are very small, often with scattered outbuildings and cars obscuring the potentially irrigated vegetation on such stands. Also, consumers in these areas are being encouraged by some to practice small-scale vegetable farming and horticulture for economic gain. Water managers should individually identify such consumers in order to ensure that an accurate estimate of their water use is used for demand forecasting and system analysis.

It was assumed for this investigation that the irrigable lawn area covers 25% of each stand and that garden beds cover an additional 13% of the area.

Garden irrigation factor

The garden irrigation factor *f* can be adjusted to represent changes in the efficiency of the irrigation system and in the habits of consumers regarding over- or under-irrigation of vegetation. The parameter is directly related to over-irrigation and indirectly related to the efficiency of the irrigation system. The value of *f* is arguably the most unpredictable of all the REUM inputs, while the garden water demand is the largest water demand contributor.

The value of *f* could be considered to vary between 0 and some higher value. If it were assumed that the irrigation efficiency is relatively close to unity, the upper value of f is determined by over-irrigation of vegetation (combined with the soil type). At some upper limit of water addition the plant will drown, because no oxygen can reach the roots.

Considering potential garden watering from boreholes and direct abstraction of groundwater by deep-rooted vegetation (such as trees) it could be expected that less than the ideal irrigation requirement of vegetation on a stand will have to be supplied by the

TABLE 2 Results for each of the five REUMcomponents (Stand A, Johannesburg, 1 000 m²)						
End-use	AADD$_i$ (kℓ/d)	AADD$_o$ (kℓ/d)	AADD$_h$ (kℓ/d)	AADF$_w$ (kℓ/d)	AADC$_w$	
					(g/d)	(mg/ℓ)
Bath	0.061	-	0.031	0.061	3	46
Bathroom Basin	0.041	-	0.020	0.041	35	842
Dishwasher	0.019	-	0.000	0.019	22	1152
Kitchen sink	0.040	-	0.020	0.040	12	299
Leaks	0.082	-	0.000	0.074	0	0
Miscl. Indoor	0.000	-	0.000	0.000	0	0
Shower	0.055	-	0.027	0.055	4	66
Toilet Large	0.159	-	0.000	0.159	505	3182
Toilet Small	-	-	-	-	-	-
Washing Machine	0.102	-	0.051	0.102	55	537
Miscl. Outdoor	-	0.015	0.000	0.000	0	0
Pool Filtering	-	0.026	0.000	0.000	0	0
Garden 1 (Lawn)	-	0.212	0.000	0.000	0	0
Garden 2 (other)	-	0.113	0.000	0.000	0	0
Garden 3 (other)	-	0.000	0.000	0.000	0	0
Pool Evaporation	-	0.054	0.000	0.000	0	0
TOTAL or AVERAGE	0.559	0.420	0.150	0.551	635	1151
AADD$_i$: +AADD$_o$	57%	43%	15%	56%	-	-

municipal supply system. Although this has not been recorded, it is also safe to assume that most consumers do not water their lawns during winter, especially in those areas where frost is common. Thus, it is likely that $f < 1.0$.

For the purpose of modelling the xeriscape WDM measures discussed in this paper each scenario is modelled with $f = 0.5$ and $f = 1.0$.

Verification of model results

Single REUM result for a typical stand

A typical suburban, residential stand was chosen to form the basis for the analyses in this paper. This stand would be the one described by the typical values presented in the companion paper for each REUM input parameter, with a few exceptions: The household size is 3 PPH, the garden irrigation factor is 0.5 and the stand size is 1 000 m². The climatological parameters pertain to Johannesburg and the garden beds are planted with vegetation having crop factors similar to that of "Tropical Bushveld" listed by Midgley et al. (1994). This baseline scenario is termed Stand A.

The results for Stand A are presented in Table 2, which includes the result for each of the five REUM components segregated by end-use. From left to right the columns represent the end-use, average annual daily water demand for indoor (AADD$_i$), outdoor (AADD$_o$) and hot water (AADD$_h$), average annual daily flow of wastewater (AADF$_w$) and the average annual daily concentration of TDS in wastewater (AADC$_w$).

The final column includes the actual mass of TDS added at each end-use to illustrate that the end-use responsible for the highest concentration of TDS in the wastewater is not necessarily the same as the one responsible for the highest mass of soluble substances added. This is apparent when comparing, for example, the values

of the washing machine and the bathroom basin. The former obviously varies depending on the wastewater flow from each end-use – a relatively larger volume of wastewater from the end-use might dilute a large mass of soluble substances added at the same end-use.

Total water demand

With reference to Table 2, the total water demand for the stand is obtained by adding the indoor demand (AADD$_i$) and outdoor demand (AADD$_o$), respectively 0.559 kℓ/d and 0.420 kℓ/d. The total is 0.979 kℓ/d. This result from the model correlates well with actual water demand estimates based on empirical guidelines presented by Jacobs et al. (2004) for the inland summer rainfall region of the country and suburban type stands. The empirical estimate for a stand of 1 000 m² (similar to Stand A) is 0.975 kℓ/d, which is almost the same as the value predicted by REUM.

Water demand by end-use

The combined contribution by the toilet, bath-shower and washing machine is 67.4% of the indoor total calculated with REUM. This compares well with values reported in the literature for the combined contribution of these end-uses to the total indoor demand: 61 to 71% (Edwards and Martin, 1995), 59 to 88% (Billings and Jones, 1996), 71 to 73% (DeOreo et al., 1996), 67% (Mayer et al., 1999), and 68% (Ball et al., 2003).

The *per capita* water demand for a conventional toilet varies from 37.5 ℓ/c·d (White et al., 1996) in Denmark to 113.6 ℓ/c·d (Baumann et al., 1998) in the USA. Most values reported vary between 40 and 60 ℓ/c·d (e.g. Edwards and Martin, 1995; DeOreo et al., 1996) and compare well with the REUM result of 52.9 ℓ/c·d.

The *per capita* water demand for a washing machine varies between 22.5 ℓ/c·d (Achttienribbe, 1998) and 79.5 ℓ/c·d (Baumann et al., 1998), with the most detailed study reporting 30.5 ℓ/c·d

(Edwards and Martin, 1995). REUM predicts 0.102 kℓ/d (a *per capita* demand of 34.1 ℓ/c·d), which agrees well with the latter value.

Values reported in literature for the *per capita* bath water demand vary from as low as 3.8 ℓ/c·d to 163.0 ℓ/c·d. This is largely dependent on whether an individual prefers to bath or shower, both of which have the same purpose (cleaning the body). Values for the *per capita* shower water demand vary from 29.4 ℓ/c·d (Achttienribbe, 1998) to 60.6 ℓ/c·d (Tchobanoglous and Burton, 1991). REUM predicts 38.7 ℓ/c·d for the bath and shower combined.

Hot water demand

Basson (1983) suggests a value of 50 ℓ/c·d for the hot water demand for a developed community in South Africa. Based on measured results for 700 stands Meyer and Tshimankinda (1997) estimate that the average annual hot water demand for medium-density houses in South Africa is 59.3 ℓ/c·d. Medium-density houses are defined in that study as those with a density of about 2 029 houses per km². The household size is reported to be 3.8 PPH. These published values agree well with the average annual hot water demand of 0.150 kℓ/d (50 ℓ/c·d) predicted by REUM for a similar type of stand.

The monthly variation in hot water demand is more pronounced according to the measurements by Meyer and Tshimankinda than predicted by REUM. The measured results indicate variation between 42 and 80 ℓ/c·d for summer and winter respectively, while REUM predicts variation between 45 and 55 ℓ/c·d respectively.

The under-prediction by REUM in winter is considered to be caused by seasonal consumer habits. For example, if larger shower and bath event volumes were applicable in winter than in summer, it would lead to an increased hot water demand in winter. However, all indoor REUM parameters are kept constant over the 12 month modelling period for the purpose of illustrating differences in this paper.

Wastewater flow

Per capita wastewater flow is reported by Tchobanoglous and Burton (1991) and Lott et al. (1999). The range of values for a single residence is 170 to 341 ℓ/c·d. The typical value from both authors is about 250 ℓ/c·d for a suburban stand, but no indication is given of whether this includes leaks.

Three components for wastewater flow (domestic water use, leaks, and infiltration), based on actual measurements and subsequent system modelling, are presented for a high-income residential area in Alberton (GLS, 2001). The results indicate a wastewater flow of 0.617 kℓ/stand·d resulting from domestic water use plus 0.259 kℓ/stand·d resulting from leaks. The average household size for high income suburbs in Alberton is 3.5 PPH (Veck and Bill, 2000). Although the two dates cited above are not the same, the change in average household size over a one-year period is considered to be negligible. The *per capita* wastewater flow is thus calculated to be 0.176 ℓ/c·d with an additional 0.074 ℓ/c·d contributed by leaks.

REUM predicts a wastewater flow of 0.551 kℓ/stand·d, or 0.184 ℓ/c·d. If leaks were excluded the value reduces to 0.159 ℓ/c·d. REUM underestimates the domestic component of wastewater flow by about 10% when compared to the Alberton data. The REUM result is on the lower end of the range when compared to the values from the USA and Australia.

Wastewater salinity

Table 2 shows that REUM predicts a total increase of 1 151 mg/ℓ in the TDS concentration between the potable water supplied to a stand and the wastewater directly downstream of the stand. This salinity increase is caused by the addition of soluble substances at the stand. It would be ideal to compare this modelled salinity increase with actual measurements for the same area. However, little research has been conducted in this regard, thus limiting the available data. Results from measured data in Australia and Cape Town are used for comparison in this paper.

Chemical analyses of wastewater from 12 wastewater treatment plants in the Western Cape were obtained (KV3, 2003). The analyses included electrical conductivity (EC) values. The latter values, converted to TDS concentrations, vary between 274 mg/ℓ and 1 482 mg/ℓ. The corresponding average TDS concentration of potable supply water varies between 50 and 250 mg/ℓ. A typical increase of about 728 mg/ℓ between the supply water and wastewater TDS concentration (received at the wastewater treatment plant) is noted, while the highest increase in concentration is 1 432 mg/ℓ.

Patterson (1994) reports TDS concentration for wastewater flow from 50 homes in Australia. The mean value is 940 mg/ℓ, with a range of 335 mg/ℓ to 3 350 mg/ℓ. The average potable supply water TDS concentration reported by the same author is 186 mg/ℓ. The increase in TDS concentration between supply water and wastewater is about 754 mg/ℓ, but the value could be as high as 3 164 mg/ℓ based on the above mentioned wastewater TDS range.

The increase of 1 151 mg/ℓ predicted by REUM is higher than the reported increases of 728 mg/ℓ and 658 mg/ℓ, as could be expected. REUM predicts the change in concentration between the points immediately upstream and downstream of a residential stand, which could be viewed as a pollution source. However, the salinity of wastewater reaching the treatment works would have been diluted by water infiltrating the sewer system downstream of the stand. However, modelling such infiltration falls beyond the scope of REUM.

Seasonal variation

Seasonal variation in water demand is a common characteristic of demand. Consultants often use peak monthly flow rates to design certain elements in a water supply system (such as treatment facilities). Such values vary between 1.2 and 1.6 times the average annual daily demand (AADD).
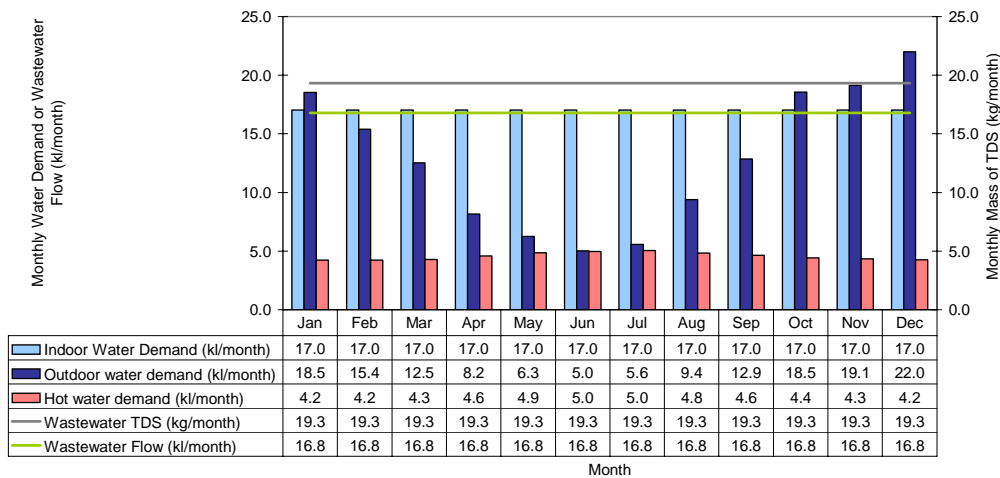
A seasonal pattern of water demand obtained from REUM is presented in Fig. 1. It distinguishes between hot and cold water to show how the hot water demand increases during the colder winter months. This cyclic pattern of hot water demand has been confirmed by previous studies. It is clear from Fig. 1 that the total water demand reaches a peak in the summer, with a peak month demand of 1.3 times the AADD.

Variation of AADD by stand size and geographic region

The influence of stand size and climatological effects on the AADD for a residential stand can be illustrated with REUM.

The water demand by stand size for stand A is presented in Fig. 2. The climatological parameters (rainfall, pan evaporation and cold water supply temperature) are varied to typify four geographic locations, namely Cape Town, George, Johannesburg and Windhoek.

The following is noted when comparing estimates based on the empirical guidelines by Jacobs et al. (2004) with REUM results for a stand size of 1 000 m²:

Figure 1
REUM results for all five components
Property: Stand A
(1 000 m²),
Johannesburg

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Indoor Water Demand (kl/month)	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
Outdoor water demand (kl/month)	18.5	15.4	12.5	8.2	6.3	5.0	5.6	9.4	12.9	18.5	19.1	22.0
Hot water demand (kl/month)	4.2	4.2	4.3	4.6	4.9	5.0	5.0	4.8	4.6	4.4	4.3	4.2
Wastewater TDS (kg/month)	19.3	19.3	19.3	19.3	19.3	19.3	19.3	19.3	19.3	19.3	19.3	19.3
Wastewater Flow (kl/month)	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
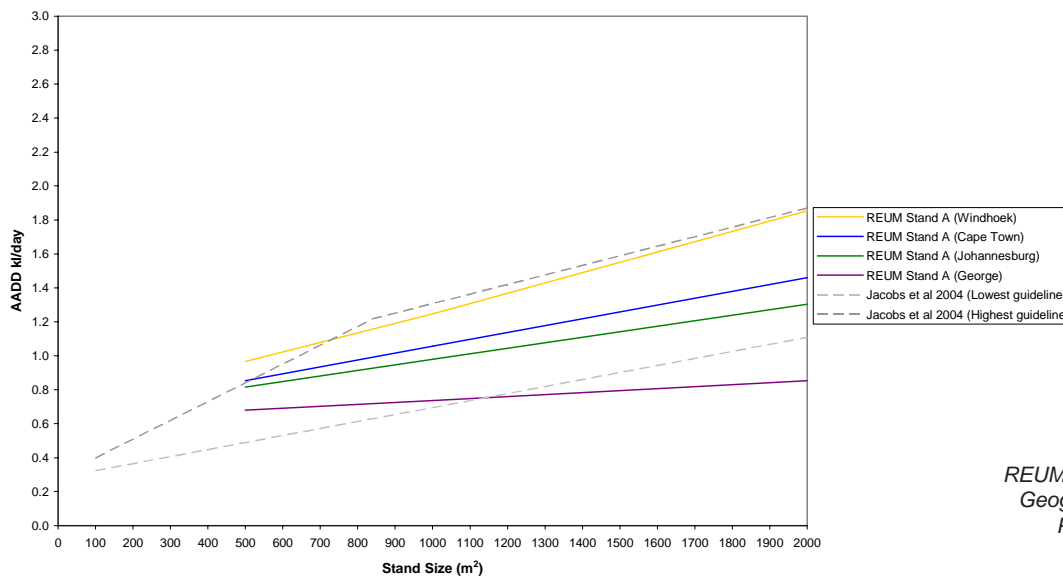
Figure 2
REUM result for AADD only -
Geographical significance
Property: Stand A

- Cape Town – the predicted result from empirical guidelines is 1.308 kℓ/d. REUM predicts 1.056 kℓ/d and under-estimates the empirical value by 19%. The most likely explanation is that home owners in Cape Town make less use of groundwater (e.g. via boreholes) than those in Johannesburg. If this were the case the value of the garden irrigation factor in REUM is too low for modelling garden water demand in Cape Town; the parameter was not adjusted to calibrate the model to the empirical estimates as part of this investigation.
- George – the REUM result is 0.737 kℓ/stand·d and is only 6% higher than the estimate based on the empirical guideline (0.695 kℓ/stand·d).
- Johannesburg – the result from empirical guidelines (0.975 kℓ/d) is almost the same as predicted by REUM (0.979 kℓ/d).
- Windhoek – the empirically estimated AADD is 1.080 kℓ/stand·d, while the predicted AADD from REUM is 1.274 kℓ/d. REUM over-estimates the water demand for Windhoek by about 15%. This over-estimate could be expected and is considered to be due to the renowned WDM programme that is in place in Windhoek (water price is reported to play a major role).

The REUM result indicates that the water demand is lowest for George, and increases for Johannesburg, Cape Town and Windhoek

in that order. The results for the modelled properties agree relatively well with the empirical guidelines, but the discrepancies for Cape Town and Windhoek show that model parameters describing human habits (e.g. actual garden irrigation volume versus theoretical garden irrigation requirements) cannot easily be populated and require further research.
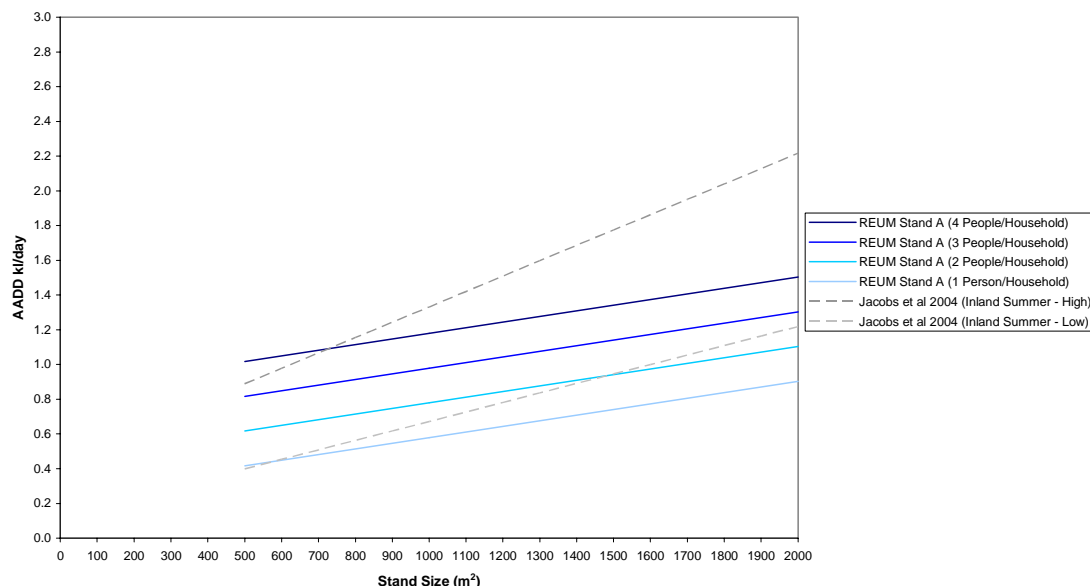
Variation of AADD by household size

The water demand for varying stand size and household size is presented in Fig. 3. The results for the stand agree relatively well with the empirical envelopes presented by Jacobs et al. (2004).

The household size is varied from 1 to 4 PPH (as discussed earlier in this paper, the *per capita* water demand is held constant). The graph clearly indicates that the water demand increases with stand size when the household size is held constant, and that an increased household size leads to an increased water demand. Figure 4 illustrates the impact of a change in household size on all five REUM components.
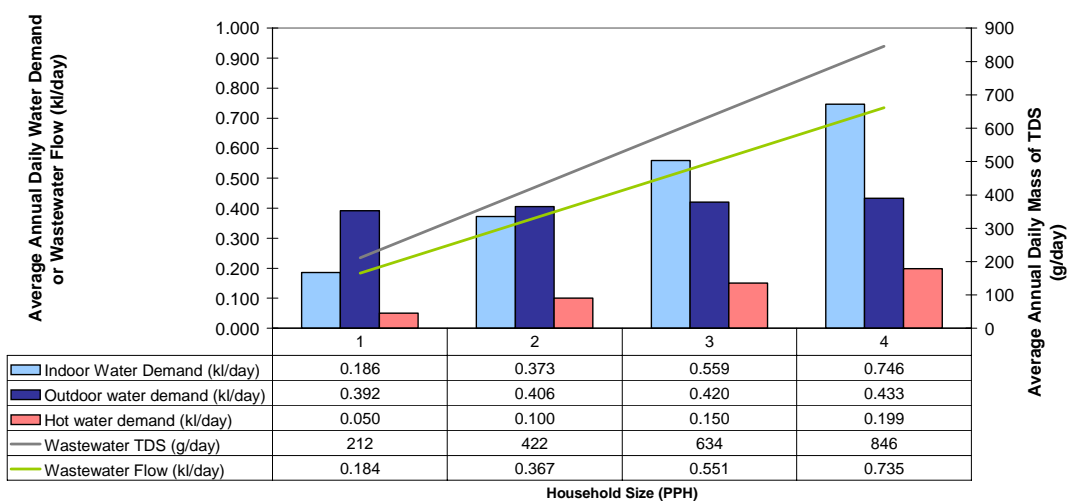
Prediction of a few WDM measures' effects

The above-mentioned results pertaining to the verification of the model as well as each WDM measure discussed in the following

Available on website **http://www.wrc.org.za**

Figure 3
REUM result for AADD only - Adjusted household size and stand size Property: Stand A, Johannesburg

Figure 4
REUM results for all five components Property: Stand A (1 000 m²), Johannesburg

	1	2	3	4
Indoor Water Demand (kl/day)	0.186	0.373	0.559	0.746
Outdoor water demand (kl/day)	0.392	0.406	0.420	0.433
Hot water demand (kl/day)	0.050	0.100	0.150	0.199
Wastewater TDS (g/day)	212	422	634	846
Wastewater Flow (kl/day)	0.184	0.367	0.551	0.735

Household Size (PPH)

section of the paper are included in Table 3. The table structure is similar to Table 2, but instead of segregating each result by end-use only the annual average result for each REUM component is presented for each scenario. The segregation by end-use as presented in Table 2 is of course available from REUM in each case.

Table 4 lists the savings brought about by some of the WDM measures when compared to the baseline property (Stand A).

Toilet retrofit

The results for two alternative WDM measures regarding reduced toilet flush volume are included in Table 3. The two alternatives are described by the following modelled properties:

*   Stand B – retrofitting a 9.0 ℓ/flush conventional toilet at Stand A where the pre-retrofit flush volume is 14.3 ℓ/flush.
*   Stand C – retrofitting a 6 to 3 ℓ/flush dual-flush toilet at Stand A (note that such a low volume dual-flush system implies a complete toilet retrofit, including cistern and pan, to ensure efficient flushing).

As could be expected the savings included in Table 4 show that the dual-flush toilet provides an increased water saving and reduced

waste water flow, but the TDS concentration is higher due to the reduced wastewater flow.

Shower nozzle retrofit

A reduced shower event volume can be obtained by retrofitting a 0.1 ℓ/s low-flow showerhead at Stand A (the same reduction could be obtained by halving the shower duration while maintaining the pre-retrofit flow rate, which implies awareness and education of end-users):

*   Stand D – a shower event volume of 30 ℓ/event in place of 60 ℓ/event for the pre-retrofit (Stand A).

Despite the use of this very low shower flow rate the water saving and impact on wastewater flow are not significant, but part of the reduced water demand is due to a saving in hot water.

Pool presence and pool cover use

As discussed earlier, the baseline property (Stand A) is modelled with a pool water surface area of 13.3 m² in order to compare the results to empirical findings for whole neighbourhoods. Two

TABLE 3
Summary of REUM results for selected WDM measures (Stand size of 1 000 m²)

Description	Property	Location	House-hold size (PPH)	AADD kℓ/d	$AADD_i$ kℓ/d	$AADD_o$ kℓ/d	$AADD_h$ kℓ/d	$AADF_w$ kℓ/d	$AADC_w$ g/ℓ	$AADC_w$ g/d
Baseline property (Garden 3)	Stand A	Cape Town	3	1.056	0.559	0.497	0.145	0.551	1315	635
Baseline property (Garden 3)	Stand A	Johannesburg	3	0.979	0.559	0.420	0.150	0.551	1315	635
Baseline property (Garden 3)	Stand A	George	3	0.737	0.559	0.178	0.147	0.551	1315	635
Baseline property (Garden 3)	Stand A	Windhoek	3	1.247	0.559	0.688	0.142	0.551	1315	635
Baseline property (Garden 3)	Stand A	Johannesburg	1	0.578	0.186	0.392	0.050	0.184	1315	212
Baseline property (Garden 3)	Stand A	Johannesburg	2	0.779	0.373	0.406	0.100	0.367	1315	422
Baseline property (Garden 3)	Stand A	Johannesburg	4	1.179	0.746	0.433	0.199	0.735	1315	846
Retrofit conventional toilet (9 ℓ/flush)	Stand B	Johannesburg	3	0.921	0.501	0.420	0.150	0.492	1453	635
Retrofit dual flush toilet (3 & 6 ℓ/flush)	Stand C	Johannesburg	3	0.867	0.447	0.420	0.150	0.439	1582	623
Retrofit low-flow showerhead (0.1 ℓ/s)	Stand D	Johannesburg	3	0.952	0.532	0.420	0.136	0.524	1375	635
No pool	Stand E	Johannesburg	3	0.925	0.559	0.366	0.150	0.551	1315	635
Pool, with pool cover in use	Stand F	Johannesburg	3	0.962	0.559	0.403	0.150	0.551	1315	635
Completely repair all leaks (leaks = 0 ℓ/d)	Stand G	Johannesburg	3	0.897	0.477	0.420	0.150	0.477	1494	635
Washing machine, detergent change	Stand H	Johannesburg	3	0.979	0.559	0.420	0.150	0.551	1216	580
Washing machine, only cold water supplied	Stand J	Johannesburg	3	0.931	0.511	0.420	0.099	0.503	1426	635
Garden 1	Stand K	Johannesburg	3	0.885	0.559	0.326	0.150	0.551	1315	635
Garden 2	Stand L	Johannesburg	3	0.926	0.559	0.367	0.150	0.551	1315	635
Garden 4	Stand M	Johannesburg	3	1.056	0.559	0.497	0.150	0.551	1315	635
Garden 5	Stand N	Johannesburg	3	1.117	0.559	0.558	0.150	0.551	1315	635
Garden 6	Stand O	Johannesburg	3	1.197	0.559	0.638	0.150	0.551	1315	635
Garden 7	Stand P	Johannesburg	3	1.304	0.559	0.745	0.150	0.551	1315	635
Garden 8	Stand Q	Johannesburg	3	1.459	0.559	0.900	0.150	0.551	1315	635
All measures combined[A]	Stand R	Johannesburg	3	0.600	0.290	0.310	0.085	0.290	2124	568

Notes :
A. That includes retrofitting a dual flush toilet (Stand C) and low-flow showerhead (Stand D), use of a pool cover (Stand F), the repair of all leaks (Stand G), a change in washing machine detergent (Stand H) and supply of only cold water to the washing machine (Stand J) plus xeriscaped garden 1 (Stand K).

alternatives are investigated to illustrate the effect of pools on the water demand and wastewater flow in a suburban neighbourhood:

- Stand E – describes complete absence of a pool (zero surface area).
- Stand F – describes the same pool as Stand A, but a pool cover is used during the winter.

The model shows that a reduction of 1.7% brought about by the use of pool covers could be expected if all pools in a neighbourhood were to use pool covers during winter. This reduction is not significant, mainly because relatively few homes have pools. Also, it is noted that pool cover use does not impact hot water demand, wastewater flow or wastewater salinity.

However, when a consumer similar to Stand A, but with a large pool (say surface area 60 m²) is modelled separately, it is found that the use of a pool cover during winter leads to a water saving of about 9%, which is substantial. The saving resulting from pool cover use varies from one geographical region to another, because it is dependent upon evaporation – the variation is significant. As an example, if the above stand were located in George a saving of only 3% would be obtained, while in Windhoek the saving would be 12%.

Repair of leaks

An example is included in this investigation to illustrate the impact of leaks on the five REUM components. The leaks are adjusted as follows:

TABLE 4 Savings due to WDM measures (Johannesburg, 3 PPH)							
Description	Scenario	AADD kℓ/d	AADD$_i$ kℓ/d	AADD$_o$ kℓ/d	AADD$_h$ kℓ/d	AADF$_w$ kℓ/d	AADC$_w$ g/ℓ
Baseline property (Garden 3)	Stand A	0.979	0.559	0.420	0.150	0.551	1315
% Saving obtained with WDM measure on baseline property (a negative value indicates an increase)							
Description	Scenario	% Saving					
Retrofit conventional toilet (9 ℓ/flush)	Stand B	5.9	10.4	0.0	0.0	10.7	-10.5
Retrofit dual flush toilet (3 & 6 ℓ/flush)	Stand C	11.4	20.0	0.0	0.0	20.3	-20.3
Retrofit low-flow showerhead (0.1ℓ/s)	Stand D	2.8	4.8	0.0	9.3	4.9	-4.5
No pool	Stand E	5.5	0.0	12.9	0.0	0.0	0.0
Pool, with pool cover in use	Stand F	1.7	0.0	4.0	0.0	0.0	0.0
Completely repair all leaks	Stand G	8.4	14.7	0.0	0.0	13.4	-13.6
Washing machine, detergent change	Stand H	0.0	0.0	0.0	0.0	0.0	7.6
Washing machine, only cold water supplied	Stand J	4.9	8.6	0.0	34.0	8.7	-8.4
Garden 1 (25% smaller lawn & 50% less beds)	Stand K	9.6	0.0	22.4	0.0	0.0	0.0
Garden 2 (25% smaller lawn)	Stand L	5.4	0.0	12.6	0.0	0.0	0.0
Garden 4 (adjust to high water use beds)	Stand M	-7.9	0.0	-18.3	0.0	0.0	0.0
Garden 5 (as for Stand K, but f = 1.0)	Stand N	-14.1	0.0	-32.9	0.0	0.0	0.0
Garden 6 (as for Stand L, but f = 1.0)	Stand O	-22.3	0.0	-51.9	0.0	0.0	0.0
Garden 7 (as for Stand A, but f = 1.0)	Stand P	-33.2	0.0	-77.4	0.0	0.0	0.0
Garden 8 (as for Stand M, but f = 1.0)	Stand Q	-49.0	0.0	-114.3	0.0	0.0	0.0
All measures combined	Stand R	38.7	48.1	26.2	43.3	47.4	-61.5
	Maximum	38.7	48.1	26.2	43.3	47.4	7.6
	Minimum	-49.0	0.0	-114.3	0.0	0.0	-61.5

• Stand G describes complete repair of all leaks by setting the parameter for leak volume equal to zero.

The results included in Table 4 illustrate that the repair of leaks impacts indoor water demand, wastewater flow and wastewater TDS concentration (hot water leaks are not modelled in REUM, neither are pressure variations).

Washing machine retrofit and detergent change

The effect of two changes at the washing machine is illustrated by modelling the following properties:

• Stand H – detergent change from an average mass of soluble substances (60 000 mg/event, as included in Stand A) to a very low mass (100 mg/event);
• Stand J – a reduced event volume obtained by retrofitting the 114 ℓ/event washing machine (which is the average event volume based on a survey) with a 60 ℓ/event machine (which is considered to be a minimum value for a modern machine) and connecting it only to the cold water supply.

The topic regarding hot vs. cold water use for clothes washing appears to be hotly debated, even by laymen. A brief survey, including 59 respondents, was conducted as part of another investigation. The aim of the survey was to:

• Establish whether it is practical to suggest that automated washing machine users wash clothes in cold water instead of hot water.

• Establish whether washing machines connect to the geyser supply, or heat water internally.

The results reflect individuals from suburban stands and the upper portion of the socio-economic profile. It is clear from both the consumer survey and a corresponding detergent study that cold water washing in automated washing machines is common in South Africa, with approximately 70% of washes being only in cold water. It is also clear from the survey that most machines (approximately 60% of the survey group) connect to the geyser supply as a source of hot water instead of heating water internally. It should also be noted that each detergent has an optimum temperature band within which it operates most effectively.

The savings summarized in Table 4 show that the detergent change reduces the wastewater TDS concentration by 7.6% and does not impact any other component of the model.

The retrofit of a new low-water use washing machine results in a low water saving of 4.9%, but a substantial hot water saving of 34.0%. The corresponding wastewater flow reduction is 8.7%, which leads to an 8.4% increase in wastewater TDS concentration.

The hot water and subsequent energy savings are only relevant if the machine is assumed to not heat the water internally, in other words cold water is used for washing instead of hot water.

Xeriscaping

Xeriscaping originates from the Greek word xeri – meaning dry. The definition provided by Colorado Springs Utilities (CSU, 2001) is, "an attractive, sustainable landscape that conserves water and is
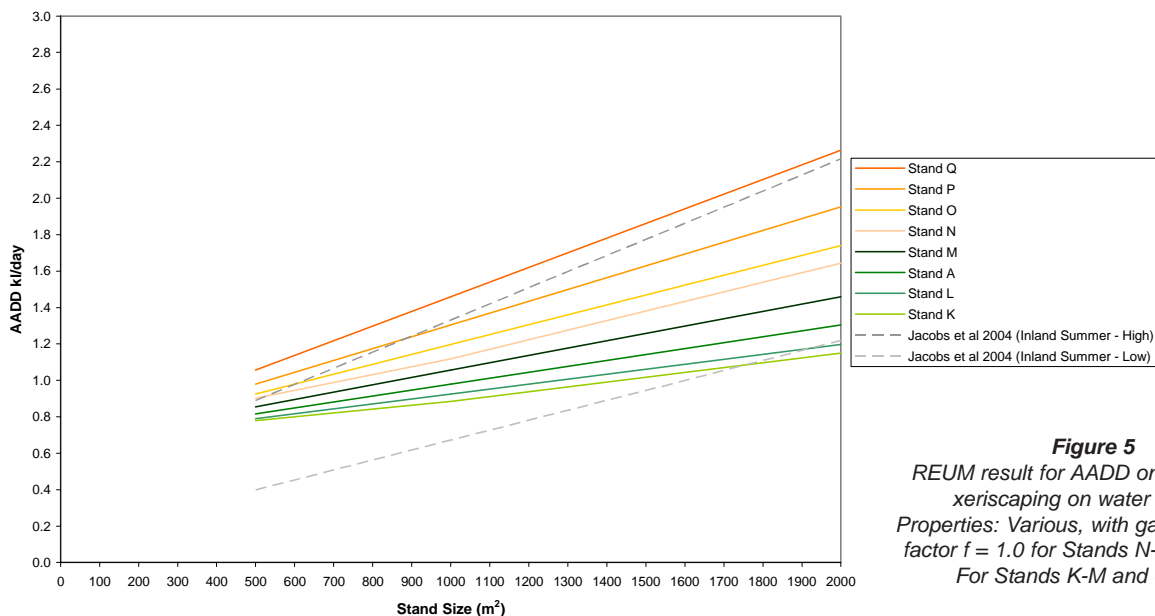
Figure 5
*REUM result for AADD only - Effect of xeriscaping on water demand
Properties: Various, with garden irrigation factor f = 1.0 for Stands N-Q and f = 0.5 For Stands K-M and Stand A*

based on sound horticultural principles". Seven so-called xeriscape principles are listed by CSU: plan and design comprehensively, evaluate soil and improve if necessary, create practical lawn areas, use appropriate plants and group plants according to water needs, water efficiently, use organic mulches, and practice appropriate maintenance.

The key elements of any xeriscape programme provided by Wasowski (2001) include:

- The use of native plant genotypes
- The reduction of lawn area
- Water saving techniques, such as more efficient irrigation systems and mulching.

In order to investigate the effect of xeriscaping on water demand, two key elements of a xeriscape programme are identified and each is evaluated by means of adjusting selected parameters in REUM. The two elements comprise the use of alternative vegetation genotypes and changing the vegetated area.

The garden of the baseline property (Stand A) consists of 250 m² kikuyu lawn plus 130 m² garden beds with vegetation similar to natural veld type "Tropical Bushveld" presented by Midgley et al. (1994). Seven alternative garden scenarios are investigated:

- Stand K – a comprehensively xeriscaped garden with 25% reduced lawn size and 50% reduced garden beds. It is considered realistic that such reductions could be obtained by boldly implementing xeriscape practices.
- Stand L – a partly xeriscaped garden where the lawn size is reduced by 25%.
- Stand M – A garden more luscious than the baseline stand, where garden bed vegetation type is replaced by "tropical forest" type vegetation.
- Stand N – as for Stand K, but the garden irrigation factor is equal to unity.
- Stand O – as for Stand L, but the garden irrigation factor is equal to unity.
- Stand P – as for Stand A, but the garden irrigation factor is equal to unity.

- Stand Q – as for Stand M, but the garden irrigation factor is equal to unity.

A change in garden type impacts only on the water demand of the stand. The hot water demand, wastewater flow and wastewater TDS concentration are unaffected by these changes. For this reason the results of the AADD only are plotted against stand size in Fig. 5. Gardening practice has not been taken into account.

The result illustrates that the vegetation genotype has a significant impact on the water demand of a residential stand, and that it has an effect on the slope of the line when AADD is plotted against stand size. The results in Fig. 5 are compared to empirical curves (Jacobs et al., 2004). The variation neatly covers the entire spectrum between the empirical envelope curves.

It should be recalled that all the REUM results presented in Fig. 5 are based on *n* = 3 PPH, understandably leading to a convergence at the upper envelope around the 500 m² stand size, where the demand is greatly driven by the indoor component.

The corresponding savings for the alternative garden scenarios are summarised in Table 4. The change in water demand brought about by the different scenarios varies from a saving of 9.6% to an increase of 49.0% when compared to the baseline property. A saving of 39.3% could be obtained if the baseline stand were the one with the highest garden water demand (Stand Q). In agreement with this Hunt et al. (1998) report that xeriscaping could reduce water demand at a stand by as much as 50%.

Plenty of other combinations of xeriscape scenarios could also be investigated with REUM.

All measures combined

The total impact of a few of the above-mentioned measures is evaluated by combining them as follows:

- Stand R – the combined implementation of the following: Retrofitting a dual-flush toilet (Stand C) and low-flow showerhead (Stand D), use of a pool cover (Stand F), the repair of all leaks (Stand G), a change in washing machine detergent (Stand H), retrofitting the washing machine and limiting its supply to cold water (Stand J) plus a comprehensively xeriscaped garden (Stand K).

Available on website **http://www.wrc.org.za**

The total impact of these combined measures on all 5 REUM components is significant.

A significant saving of 38.7% on the water demand of the baseline property (Stand A) is achieved by implementing these measures. It should be noted that Stand A is modelled with a relatively low garden water demand when compared to some of the other garden scenarios.

A saving of 43.3 % on hot water demand can be achieved by retrofitting the showerhead with a low flow nozzle and using only cold water supply for the washing machine (i.e. wash clothes in cold water instead of hot water). This would result in additional saving of energy as well.

The wastewater flow is predicted to reduce by 47.4 % if these measures were implemented. This is contributed mainly by the reduced flow from the toilet, leaks and the washing machine.

An integral and significant increase of 61.5% is predicted by REUM for the TDS concentration in wastewater. This increase occurs despite the fact that Stand R includes a smaller mass of soluble substances in the washing machine detergent.

Calibration options

A "manual" heuristic approach implying trial and error adjustment of each REUM input parameter value, within reasonable limits, could be applied to manually calibrate REUM to measured results. However, the applicability of more comprehensive methods, such as a detailed deterministic approach and genetic algorithms, could be investigated as well in future.

Further work

REUM is a tool that encourages further work and opens up numerous possibilities for research in the water demand and wastewater fields. Further work could include:

- Sensitivity analysis of all parameters with the development of an index to measure the "importance" of each parameter
- Measurement of actual results for all 5 components as well as the REUM input parameters in order to calibrate the model to actual results
- Stochastic investigation into different WDM measures by means of Monte Carlo simulation – distribution functions could be established for each REUM input parameter
- Investigation of the reuse potential and the use of hot water demand to estimate reuse potential
- Consumer education regarding the use of more "friendly" household products (containing less soluble substances)
- Continued investigation into the TDS addition at each end-use – with the wide ranges recorded it is very difficult to deliver reliable results for the wastewater salinity, unless the human habits pertaining to TDS addition are well described
- The effect of human behavioural patterns on water demand for gardening, showering and clothes washing as well as TDS addition at each end-use
- The number of end-use appliances in homes for different living standard measurement (LSM) groups
- Continued investigation into leaks (i.e. so-called plumbing leaks)
- Continued investigation into garden water demand, with particular reference to crop factors for vegetation in gardens on residential properties
- Continued investigation into monthly rainfall and temperature to also evaluate long-term climatic changes in different regions of the country

Conclusion

The number of people per household is a strong driving force for indoor water demand, while for suburban stands with irrigated gardens moisture deficit (effective rainfall minus evaporation) is a strong driving force for outdoor water demand.

REUM indicates that a large number of parameters influence water demand, hot water demand, waste water flow and waste water TDS concentration, but that it is possible to estimate values for each of these parameters and apply the end-use concept practically. Future calibration of the model would further increase the accuracy and subsequently lead to wider practical application. Discrepancies between model results and empirical data are ascribed to the fact that unpredictable and varying human habits are not easily converted to parameters, which are required as inputs to the model – this is particularly relevant when predicting garden water demand.

Two key elements of xeriscaping were investigated and the results indicate that plant genotypes have significant impact on outdoor (and total) water demand. Xeriscaping is an option that clearly holds promise for water saving from the viewpoint of WDM.

Retrofitting a good quality dual-flush toilet significantly reduces water demand, but a corresponding significant increase in the wastewater TDS concentration is noted. In South Africa dual-flush toilets are not yet a common commodity, while in the UK it was reported (Grant and Howarth, 2003) that almost 80% of all toilet sales are of the dual flush type. The need to double-flush was not noted to be a problem for dual-flush toilet types tested in other studies in Western countries, which are considered to be comparable to suburban type stands in South Africa. Retrofitting dual-flush toilets is considered to be more appropriate for suburban households, while a reduced flush frequency is more appropriate for township-type stands (where retrofitting dual-flush toilets often proves ineffective).

The installation of a low-flow showerhead leads to a reduction in water demand, hot water demand and wastewater flow. Obviously the advantage obtained depends on the habits of the particular household.

The WDM measures discussed in this paper go hand-in-hand with a mindset change, which is brought about by education, training and by means of example from educated consumers. Also, many of these appliances are not readily available in South Africa at present, but an increased demand for these products is likely to change this scenario in future.

The examples illustrated in this paper show the powerful nature of an end-use model. REUM is a cost-effective (free) tool for evaluation of WDM measures' effect on water demand and wastewater pertaining to a specific stand and a particular geographic location, described by a fixed set of input parameters. Hitherto untried WDM measures could also be evaluated by adjusting model parameters for a hypothetic device.

The structure proposed for REUM, and the practical application thereof, could be integrated into existing software packages for water demand and system analysis in order to extend the flexibility and applicability of such packages.

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