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Defining domestic water consumption based on personal water use activities

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ABSTRACT

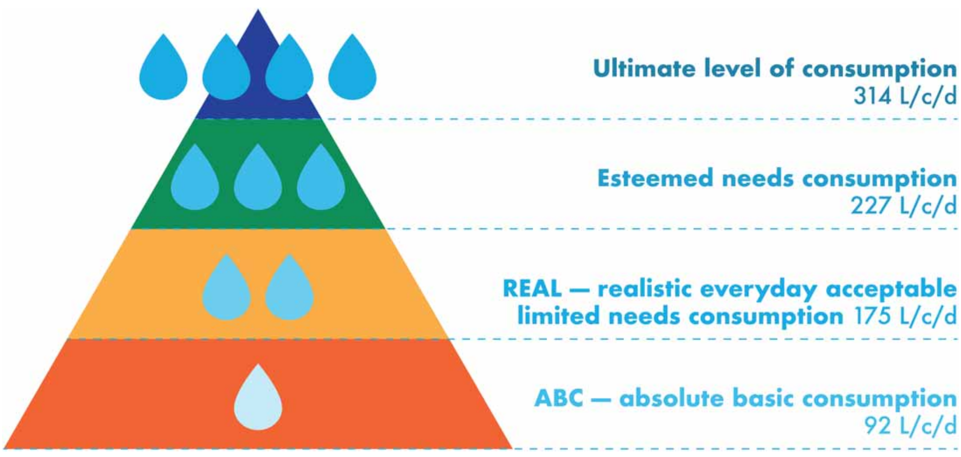
As the world increasingly faces water shortages, it is critical to develop realistic estimates of water consumption based on water-use activities rather than top-down imposed limits. This study quantifies the absolute basic consumption (ABC) of an individual, irrespective of water-use location or water source, with a focus on personal water-use activities rather than measured household consumption. A theoretical model to stochastically describe 21 personal water-use activities was developed, corresponding to lifestyle levels based upon Maslow's hierarchy of physiological needs. From this model, the expected value of ABC was 92 L/capita/day (LPCD) and includes restrictions on several everyday activities and thus would be better as a minimum target during stringent water restrictions. A more realistic expected value for non-wasteful, indoor-only water use was determined to be 175 LPCD. The results of this study serve as a useful benchmark to inform policy choices and efforts to conserve water without affecting health and wellbeing.

Key words: drinking water, stochastic model, sustainable urban development, water consumption, water demand, water-use activities

HIGHLIGHTS

- It is important to quantify water consumption based on water-use activities and across all daily water-use locations.
- The expected value of basic water consumption for a healthy urban lifestyle is 92 L/person/day, which includes restrictions on everyday activities.
- A more realistic expected value for water consumption is 175 L/person/day across all water-use locations during a typical day.

GRAPHICAL ABSTRACT



INTRODUCTION

Resource management, particularly water, is a key challenge to urban sustainability. The supply of adequate water is essential to ensure healthy urban living, but access to clean water still evades millions of people around the globe (WHO and UNICEF 2021). At a basic level, water is required for direct consumption, food preparation as well as for hygiene purposes. A number of recent drought emergencies around the world, notably the City of Cape Town's 'Day Zero' crisis, have brought greater attention to the need to reduce water use and quantify the minimum water needs for urban residents (Booysen *et al.* 2019). In contrast, the COVID-19 world health crisis of 2020–2021 has placed emphasis on hygiene in general – also regular and proper hand washing and cleaning of surfaces – in order to prevent or minimise the spread of infectious diseases. Even absent a crisis, many jurisdictions are moving to establish targets for maximum domestic water consumption (e.g. Defra 2019), but these targets can often represent arbitrary ideal values.

While it is critical to understand and limit water wastage, the current approaches to addressing household water consumption focus almost exclusively on driving down demand, with a focus on water-use appliances and fixtures – without considering human needs and the personal water-use activities that these products enable. It is these water-use activities that deliver a variety of benefits for public health (e.g. hand washing, sanitation, cleanliness) and wellbeing (e.g. gardening, pet care, relaxation, physical exercise) that are associated with an elevated standard of modern urban living.

Context and limitations

This paper presents a method for exploring water requirements in the context of modern living standards as a benchmark for holistically understanding water needs, given current technology, so that efforts to promote water efficiency are realistic and do not adversely impact health and wellbeing. Individual domestic water use was described in this study as a function of specific water-use activities, each linked to stochastic input parameters. Other variables that are known to affect household water use, such as price (e.g., Howe & Linaweaver 1967), income (e.g., DHS 2019), plot area (e.g., Makwiza & Jacobs 2016), and rainfall (e.g., Linaweaver *et al.* 1963), were purposefully excluded. The focus in this study was on the individual's personal water-use activities in any setting (at home, the office, a restaurant, the gymnasium, etc.) instead of water use at a fixed location and cost, i.e. at the particular home. Also, the impact of the different consumption levels on the water service provider, for example on the utility revenue due to reduced water sales, was considered beyond the scope of this study.

Minimum water requirements

Humans have the right to 'sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses' (United Nations Committee on Economic Social and Cultural Right 2003). A minimum quantity of water should be available for drinking, food preparation, basic hygiene, bathing and sanitation to ensure sustainable, healthy urban living. The most basic water requirement is stipulated by the World Health Organization (WHO) and varies between 20 and 50 litres per capita per day (LPCD). The basic water requirement determined by the WHO is limited to access at an offsite tap and does not include consideration of homes with piped water (WHO 2003). For this study, water use is viewed from the perspective of sustainable, healthy urban living which implies a higher level of service than the minimum required to survive, that is a full household connection to continuously supplied, piped, pressurised, potable water. Water quality considerations were beyond the scope of this study.

Water use and human needs

Willis *et al.* (2011) classified types of household water uses as being non-discretionary or discretionary, although this distinction is subjective and context-specific. Under this definition, non-discretionary water use is 40–70 LPCD and any water use above this value should be considered discretionary water use, irrespective of what it is being used for. A number of studies have examined household water use, using metering data, surveys and other methods, yielding typical values from 93 LPCD (Athuraliya *et al.* 2012) to 430 LPCD (Hay *et al.* 2012). Biswas & Gangwar (2020) reported that water supply in Delhi, India, varies from 29 LPCD in regions with poor service to 509 LPCD in the privileged residential zones. A key determinant in these reported values is the extent of outdoor water use, which can vary significantly based upon the local climate and building preferences, making it difficult to compare values from different areas and different studies. Also, water demand management and conservation efforts could lead to more efficient use of water (Adler 2011), with related water reduction. However, such efficiency improvements are limited by aspects such as current practices, behaviour, available technology and affordability. Reducing water consumption via demand management practices without impacting the level of service provided to consumers and without negatively affecting healthy, sustainable urban living is a genuine challenge for sustainable cities. In view of the above, a framework is needed to link water use to the expectation of end-users.

Maslow's hierarchy of human needs is a useful framework in which to consider water-use requirements. Humans have different levels of needs, defined by Maslow in a hierarchy ranging from basic physiological needs, safety, love and belonging, and esteem to the highest level of self-actualisation, which is defined as achieving one's full potential (Maslow 1943). Basic needs for water consumption to fulfil baseline physiological and safety needs would include drinking water, cooking uses, basic hygiene, and sanitation. Higher level needs for esteem and self-fulfilment would include additional water uses associated with sparkling clean homes and belongings, water-related sports or relaxation activities requiring swimming pools and hot tubs and irrigated gardens. Clayton (2007) found that gardening has important positive effects on individuals, as well as on the urban ecosystem. Outdoor use can support seasonal small-scale horticultural crops in backyards (Makwiza & Jacobs 2016) and improve general wellbeing, which contribute to overall quality of life.

Water use is intricately linked to health and hygiene (Prüss-Üstün *et al.* 2008; WHO 2019), with insufficient water services leading to diseases such as diarrhoea or other faecal-orally transmitted diseases, skin and eye infections (Bradley 1977). Hand washing, particularly with increased frequency and duration as was recommended to reduce the spread of coronavirus, is a key element of hygiene that uses clean water. Many household activities require hand washing to maintain hygiene and avoid the spread of contamination including contact with an infected person, handling food, coughing or sneezing, making use of the toilet, handling laundry items, handling domestic animals, disposing of household refuse, or caring for an infant. Furthermore, it is essential to regularly clean clothes and household linen as well as surfaces, floors, and household furniture to maintain optimal hygiene (RSPH 2019).

Several countries have had water efficiency legislation in place for decades, although this typically focuses on water efficiency labelling requirements for specific water-use products such as toilets and appliances (AS/NZS 2016; USEPA 2020). A few examples are presented here, but this list is not comprehensive. UK Building Regulations currently require that all new homes are built to a water consumption standard of 125 LPCD, with an optional standard of 110 LPCD which can be applied by local authorities in water-stressed areas and has been adopted by approximately 100 areas across the UK (HM Government 2016). Biswas & Gangwar (2020) report on norms and benchmarks prepared by various public institutions in India and report a requirement of 227 LPCD. South African guidelines allow for supply of 25 LPCD for communal standpipes to 400 LPCD for high-income residential areas (DHS 2019).

Like the water efficiency labelling programmes, many building regulation calculators focus on the water-use products and assign a factor for daily usage to each one and, therefore, is best suited for the design of new buildings rather than realistic representation of actual water consumption. The UK Building Regulations (HM Government 2016) acknowledge that human behaviour will influence actual water consumption and as such, these guidelines should not be used for water supply calculations.

Water loss and leakage occur in residential homes from time to time (Lugoma *et al.* 2012; Meyer *et al.* 2018), where a number of water fixtures and plumbing can leak and often remain undetected. It is often unclear whether allowance for water loss and leakage is included in LPCD values as presented in the published guidelines. Water losses may also be attributed to recommended practices in households such as flushing of lead pipes before drinking the water, which can equate to a loss of 5–20 L per event (Speight 2018), and to wasted water while users wait for a suitable temperature from hot water taps, which has been estimated to be as high as 15 LPCD (Nawaz & Waya 2014). Every home and lifestyle level is subject to a certain degree of water loss and leakage, as are the piped distribution networks which deliver water to households. Ageing infrastructure is a problem in many countries around the world and will exacerbate leakage. In many cases, the network leakage represents a volume similar to an individual's domestic water use. For example, in the UK an estimated 3.1 billion litres per day of water is lost through leakage, which represents 121 L per household per day when averaged across the 26.2 million households served (Water UK 2019). Therefore, efforts to promote water efficiency need to take a balanced approach that considers the impact on health and wellbeing of consumers within the wider context of the water utility's supply and leakage situation; this study addresses this need by developing a stochastic model for individual water use across typical urban water-use activities.

METHODS

A stochastic model comprising 21 water-use activities described by 135 model input parameters was developed in this study to model per capita personal water use, named the LPCD model. The model input parameters drew upon the published literature for household water use and a survey which covered 11 countries worldwide. A comprehensive description of the development of the model is given in Crouch (2020).

The modelling methodology identified water-use activities and their associated water-use requirements, linked these water-use activities to lifestyle levels, and developed probability distributions for the occurrence of each water-use activity. This study quantifies the water use of an individual, irrespective of water-use location or water source, with a focus on personal water-use activities rather than measured household consumption. Monte Carlo simulations of 100,000 households were performed using the @Risk software in MS Excel for each lifestyle level to determine the expected value of individual water use under the given conditions.

Description of water-use activities

A water-use activity was defined in this study as the specific activity, either indoor or outdoor, for which water is used. Showering, washing clothes, cleaning the house, and car washing are examples of water-use activities. The supply of the water does not have to originate at the point of the activity. For example, a bucket of water can be drawn from the kitchen, shower, or bath tap and used for washing the floors of the house. The water-use activity, in this case, would be cleaning the house.

A water-use activity differs from the commonly encountered water end-use. An end-use is the appliance or plumbing fixture that serves as the water exit point (e.g. tap), regardless of the activity for which the water is being used. Following the previous example, the end-use would be the kitchen, shower, or bath tap, whereas the water-use activity would be cleaning the house. Some water-use activities are intrinsically associated with appliances or fixtures, including dishwashing using a dishwasher, laundry using a washing machine, shower, and toilet.

Domestic water use is affected by a number of factors, including the age, occupation, cultural preferences, and household income of the individuals using water. For example, the age of the occupants affects water use as the activities of an individual change with age and their associated lifestyle (Browne *et al.* 2014). When showers are used, children and teens have been found to shower for longer than adults, thus increasing household water use (Mayer *et al.* 1999). In Germany, household water use has also been found to increase with age, often because the elderly who are retired spend more time in the house, which implies an increased likelihood to use water while at home (Schleich & Hillenbrand 2009). For this study, such factors were not explicitly modelled, because water use in this study was not linked to spatial attributes – relevant factors were instead considered in the development of the appropriate stochastic representation of water-use activities.

Based upon the literature from a number of studies on individual water-use activities, household water use, and water end-use, the frequency and volume associated with each of the 21 water-use activities were estimated along with the penetration of the technology. Full details are provided in Supplementary Table S1 and Figures S1–S7.

Lifestyle levels

Based upon Maslow's hierarchy of human needs, five lifestyle levels for water consumption were developed. The first is the minimum water use for basic survival, as defined by the WHO (2003) and similar studies. Typically, the minimum water use does not apply to piped water systems and excludes any outdoor water use.

The second lifestyle level, corresponding to Maslow's second level which includes safety as well as basic physiological well-being, is defined as the absolute basic consumption (ABC). The ABC can be considered in this study as the minimum personal daily indoor water requirement for a healthy modern urban lifestyle and was so designated to represent a scenario of water restrictions during a drought or living in a water scarce climate. Outdoor water use, including garden irrigation, swimming pool maintenance, car washing, and cleaning of sports equipment, was not deemed a necessity when considering the minimum water requirements for the ABC lifestyle level.

The realistic everyday allowable level (REAL) consumption was defined to include additional water use to support a more comfortable modern lifestyle than would be the case under ABC, but still excluding outdoor water use. Leakage and water loss were excluded from these lifestyle levels to focus exclusively on the calculation of indoor water use. In cases where leakage is known to be significant, it should be added separately to the ABC and REAL consumption values.

The highest two levels are esteem, which expands upon the uses allowed for REAL consumption and permits some outdoor water use and accounts for leakage, and ultimate, which is unrestricted water use. Leakage and water losses do regularly occur in pipes, toilets, taps, geysers, and swimming pools, at some stage and to some degree, in all households. While leakage and water losses can account for 10–20% of household water use, only 17% of households have significant leakages (Heinrich 2009; Water Corporation 2010), so the leakage impacts were restricted to esteem and ultimate lifestyle levels.

A summary description of the water uses associated with lifestyle levels ABC through ultimate is given in Table 1, with full details of the water-use activities for the REAL level provided in Supplementary Table S1.

Restrictions for ABC versus REAL consumption

The development of the ABC and REAL lifestyle levels depicts a relatively conservative water use (REAL) and the absolute minimum water use (ABC). The REAL lifestyle level was set up to allow for indoor water use with minimal restrictions, but with no outdoor water use permitted. However, to achieve the ABC lifestyle level within an urban household, serious lifestyle changes would be required such as eliminating indoor plants and shaving. A number of water-use appliances were assumed to be at high efficiency for the ABC lifestyle level, which in reality would require retrofitting and a cost implication. A comparison of the affected water-use activities for the REAL and the ABC lifestyle levels is given in Table 2.

Household size

Household size varies notably and contributes significantly to domestic water use, having been found to be the most significant factor affecting total household water use (Rathnayaka *et al.* 2014). The per capita water use of a household decreases as the household size increases, because many water-use activities benefit multiple household members, such as washing machines, cleaning, dishwashers, and cooking.

For simplicity, the baseline LCD model assumed a single-person household. The water use for multi-person households could be approximated by the following equation (Jacobs 2004):

$$\text{Per capita water use} = \text{SPC} \times d^{-0.439} \qquad (1)$$

where SPC is the single-person household LPCD and d is the household size.

Table 1 | Summary of water-use activities included in each lifestyle level

	Lifestyle level			
Water-use activity	**ABC**	**REAL**	**Esteemed**	**Ultimate**
Toilet	Yes[a]	Yes	Yes	Yes
Shower	Yes[a]	Yes	Yes	Yes
Bath	Yes[a]	Yes	Yes	Yes
Clothes washing	Yes	Yes	Yes	Yes
Dishwasher	Yes	Yes	Yes	Yes
Washing dishes by hand	Yes	Yes	Yes	Yes
Drinking water	Yes	Yes	Yes	Yes
Cooking	Yes	Yes	Yes	Yes
Eyecare	Yes	Yes	Yes	Yes
Hand washing	Yes[a]	Yes	Yes	Yes
Shaving	No	Yes	Yes	Yes
Brushing teeth	Yes[a]	Yes	Yes	Yes
Cleaning the house	Yes	Yes	Yes	Yes
Wiping kitchen counter	Yes	Yes	Yes	Yes
Indoor plants	No	Yes	Yes	Yes
Pets	Yes	Yes	Yes	Yes
Irrigation	No	No	Yes[a]	Yes
Carwash	No	No	Yes[a]	Yes
Swimming pool	No	No	Yes[a]	Yes
Leaks	No	No	Yes	Yes
Miscellaneous	Yes[a]	Yes[a]	Yes	Yes

[a]Restrictions were applied, see Table 2.

Table 2 | Restrictions on water-use activities for REAL and ABC lifestyle levels

Water-use activity	ABC lifestyle level	REAL lifestyle level
Toilet	All toilets with a flush volume of greater than 4.5/9.0 L dual flush or 6 L single flush must be retrofitted with a water-saving toilet	Allows for any toilet flush volume
	Toilet flush frequency was limited to two times a day	Toilet flush frequency was not limited
Shower	Shower heads must be retrofitted with a low flow shower head with a flow rate of less than 9 L/min	No restrictions placed on shower head flow rate
	Shower duration was limited to a mean of 3 min and a maximum of 6 min	Shower duration was assessed considering average shower duration
Bath	Bath volume limited to less than 60 L/event	Bath volume limited only by bath size
	No baths for relaxation were allowed	Occasional baths for the purpose of relaxation were allowed
Hand washing	Faucets must be retrofitted with low flow faucets with a flow rate of less than 9 L/min, yet it is recommended to try keep the faucet flow rate less than 6 L/min	No restrictions placed on faucet flow rate
	Water-based hand washing frequency reduced by 30% and replaced with the use of waterless hand sanitisers	Water-based hand washing frequency was dictated by daily activities
Shaving	Shaving with water was not allowed, so an alternative waterless means of shaving would be required	Any means of shaving allowed
Brushing teeth	The volume of water used for teeth brushing was restricted to the beaker technique, resulting in a maximum volume of 0.6 L/event	The average teeth brushing volume allowed
Miscellaneous	A maximum of 10 L of water once a month was allowed for miscellaneous or emergency use	Water use for activities such as cleaning the fridge, house windows, doing clean/sanitise runs of the dishwasher, and washing machine allowed

RESULTS AND DISCUSSION

The model results for a single-person household yield an expected value for REAL consumption of 175 LPCD, with a normal range of 100–251 LPCD (Table 3). The ABC represents a 47% decrease in water use from the REAL lifestyle level, with an expected normal range for ABC of 52–132 LPCD, defined as the mean plus or minus one standard deviation. The stochastic nature of this model means that there is overlap between the REAL and ABC lifestyle levels, which depend on the specific water-use activities that were included in each simulation. These results indicate that in dire situations, placing severe restrictions on water use could result in a reduction in water use of up to 47% from normal indoor water use. However, there would be considerable cost and lifestyle habit implications, including retrofit of appliances and limited water use for various activities. In view of additional hygiene requirements that would be linked to a pandemic (e.g. Covid-19), the ABC would be unachievable.

The results (Table 3) were compared to the literature values reported from over 100 international studies for per capita water use ranked from lowest to highest, as shown in Figure 1. The mean ABC is consistent with the lowest reported per

Table 3 | Predicted water use for a single-person household at each lifestyle level

	Predicted water use by lifestyle level (LPCD)			
Statistic	**ABC**	**REAL**	**Esteemed needs**	**Ultimate**
Mean	92	175	227	314
Standard deviation	40	75	94	179
Maximum	690	1,434	1,720	1,937
Normal use range	52–132	100–251	133–321	135–493

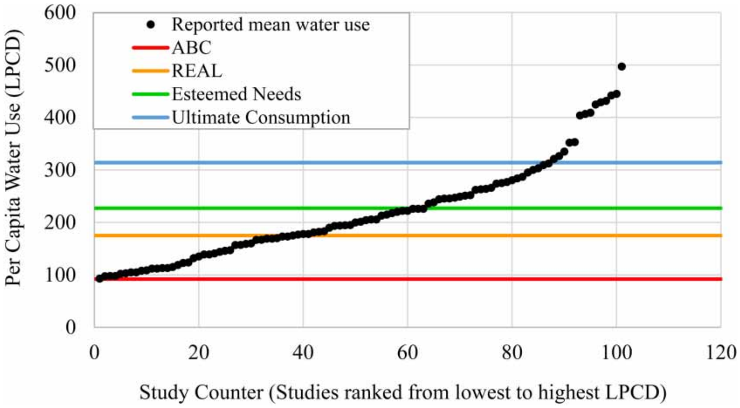


Figure 1 | Comparison of predicted water use to literature values for per capita water use.

capita water use, which reinforces the restricted nature of the requirements to achieve the ABC level. The ultimate consumption lifestyle-level expected value is lower than several studies. The predicted normal use range for the ultimate level encompasses all but the single highest reported per capita water use. The LCD model delivers a realistic and representative prediction of individual water use when compared with numerous previous studies.

The results were adjusted for an increase in household size by using Equation (1), with maximum household size being limited to five people per household in this analysis. The results of the expected per capita consumption with increase in household size, for each lifestyle level, are given in Figure 2. The per capita water use decreases with an increasing number of household members, and the biggest difference observed is for the ultimate lifestyle level where large water uses such as outdoor irrigation are mitigated by providing benefit to a larger number of people. The ABC lifestyle level is able to meet a target of 50 LPCD, which was the goal during the Cape Town 'Day Zero' extreme drought, when the household size is increased to five people.

The results of this study demonstrate that one-time initiatives providing incentives to retrofit old toilets, shower heads, and faucets may reduce the average indoor water use, but to remain at the ABC level of 92 LPCD, lifestyle changes are also necessary. The lifestyle changes selected for this analysis include: only flushing the toilet twice per day, never shaving with water, using the beaker technique to brush teeth, using hand sanitiser to wash hands when they are not soiled, and limiting showers to 3 min regardless of water temperature. Many of these practices have been included in drought management plans around the world and are tolerated by water users in the short term but would not be considered desirable on a permanent basis. For the current developed world lifestyle and typical household water-use fixtures, the REAL lifestyle level of water consumption of 175 LPCD is more realistic – in cases where outdoor use could be completely banned.

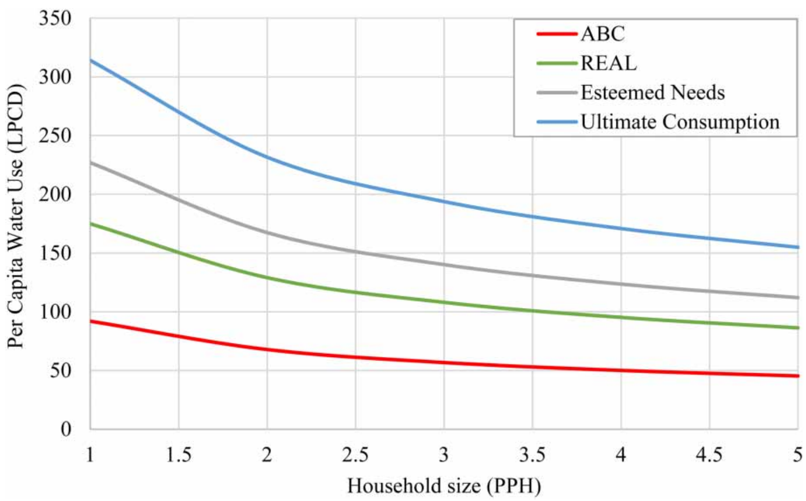


Figure 2 | Predicted water use adjusted for household size.

Consideration should also be made for location. The ABC and REAL lifestyle levels do not account for any outdoor water use, including water to wash cars. For households with no outdoor spaces and/or cars, achieving REAL consumption levels is realistic. However, in countries where outdoor green spaces require irrigation, completely restricting outdoor water use to achieve reduced water consumption may prove socially unacceptable, or even impossible in the long term. Many water scarce parts of the world already restrict outdoor usage to certain days to help manage the impact of this potentially large area of water consumption. But as urban gardening grows in popularity, especially for food production, and climate change impacts necessitate more irrigation (Makwiza *et al.* 2018), outdoor urban water use will become more contentious, particularly if potable water sources are to be used for this purpose.

CONCLUSIONS

The approach taken in this study to focus on water-use activities rather than measured household water consumption makes an important advance into understanding realistic ways to conserve water. However, some variables known to affect demand were thus not considered in this study (e.g., water price and garden size). The LCD model with the four lifestyle levels of consumption that were defined in this study illustrate a range of possible choices in terms of restrictions for different water-use activities, but other options could be modelled to evaluate policy choices and their impact on individual water consumption.

The quantification of ABC for healthy urban living was based on current technology, ignoring potential future efficiency improvements and leakage. The resulting ABC of 92 LPCD for a single-person household places a number of lifestyle restrictions on consumers. The long-term sustainability of consumption at such a level using current technology is a concern and hygiene would be negatively impacted through reduced toilet flushing and hand washing. Thus, it is more appropriate that the ABC consumption level be considered as a short-term solution in times of severe water scarcity or until efficiency improvements become available. A more feasible lifestyle level for urban water users with indoor water use only is the REAL consumption, with an expected value of 175 LPCD for a single-person household. Many European countries have already achieved an average per capita water consumption lower than this value without compromising a healthy urban lifestyle, although national consumption values reflect a majority of multi-person households. For a two-person or three-person household, the REAL consumption equates to 129 and 108 LPCD, respectively. A national target for water efficiency within this range seems realistic for areas where outdoor water use could be eliminated.

There is a need to take a holistic view of water use, including leakage and other inefficiencies, to meet future challenges with regard to water scarcity and healthy urban living. A focus solely on household consumption, often as quantified through consumer meter readings, fails to capture the wide range of water-use activities that an individual performs away from the household. An important consideration for policy-makers is that a strong emphasis on reduction of household consumption can increase water consumption away from the home, e.g., in the office, shopping centres, sports facilities, and gyms. The offsite use of water for household activities could lead to increased water use per person, because the person using the water does not pay for consumption away from home. Anecdotally, during the Cape Town drought as increased scrutiny was placed on metered household water consumption, people began to shower at work or the gym to avoid the appearance of high water consumption and related fines at home (the authors had first-hand experience of this). The issue of water consumption at non-domestic locations also reinforces the need to consider water conservation at commercial and industrial premises, where measures such as water recycling at commercial car washes can deliver water savings to a large number of individuals and preserve potable sources for water-use activities that require the cleanest water.

The ABC level of consumption could imply lifestyle changes that are not feasible, given current practices, available technology, affordability, and the levels of service expected by urban consumers in many developed countries. A more feasible lifestyle level for urban water users with indoor water use only is the REAL consumption, with an expected value of 175 LPCD for a single-person household. This study was not done with the assumption that the lifestyle levels or specific water-use activities could be dictated, but rather to inform the kinds of lifestyle changes that may be required in relation to future water-use targets issued by authorities.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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