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UNDERSTANDING THE PERFORMANCE OF IRRIGATION SYSTEMS AROUND HOMES

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Abstract. This study examines factors that affect the efficiency of outdoor home irrigation in the Sydney Metropolitan Area (SMA). The irrigation systems of 50 home sites were monitored, over a five-month period for flow rate, start time, duration and irrigation date. The monitoring was for quantification of the water use for lawn, garden and other garden areas, understanding of the issues and factors that affect the performance of irrigation. Results show that hand watering was the most common method, accounting for 35% of the areas irrigated by homeowners. Both portable sprinklers and microjets accounted for 20% and fixed sprinklers and drip irrigation accounting for 11% and 8% respectively. The study has implications for developing suitable urban water management strategies, and significant opportunities exist for water conservation through appropriately designed educational programs and the installation of improved irrigation systems, especially for the areas that are smaller or used for home gardens.

Keywords: urban water use, gardening, water management, urban irrigation, irrigation and sustainability.

Introduction

Access to adequate fresh water supplies for human consumption and the environment is one of the greatest challenges we face in urban landscapes in this century. Population and economic growth, including land use changes around urban areas, possible climate change and water quality degradation could have far reaching effects on future water supplies, thus further aggravating the situation of global water security. In particular, people in developing countries will particularly find water scarcity difficult to cope with due to their larger population base and limited resources for water infrastructures (Postel *et al.* 1996). Urban communities are therefore increasingly realising the need to save potable water supplies, while government agencies continue to look for appropriate water conservation plans and strategies that will allow continued economic development in the face of competition for limited and, in some cases, dwindling regional water resources. For effective water resource planning and policy development, understanding the factors that affect urban water consumption will be critical (Bouwer 1994; De Oliver 1999; Gutzler, Nims 2005; Hurd 2006; Hanak, Browne 2006; Endter-Wada *et al.* 2008; Harlan *et al.* 2009).

Water is required for a number of activities in urban environments and it is important for sustaining quality of life and economic activities. In particular, water for urban irrigation plays an important role in maintaining aesthetics, shading, screening, or other desired qualities of the urban environment and in general providing social and ecological services (Cook *et al.* 2012). Gardens and gardening play a significant role in the urban lifestyle and as such to a large extent they determine the water use outside the home. There is now a significant evidence in the literature suggesting the relationship between home gardens and the quality of life, particularly their role in prevention of stress, recreation activities and personal and social identity (Syme *et al.* 2004). The extent of water saving through proper irrigation system designs and maintenance can be substantial and the savings can reduce the need for alternative water supply sources such as desalination. Therefore, reducing water use of high-end consumption is possibly the most important driver of water conservation (Ferguson 1987; Arbues *et al.* 2003; The Barton Group 2005).

Water supply for many cities in Australia has been at a critical level for more than five years and there is a

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need to use water more wisely and efficiently. With water supplies declining and demand for water increasing due to new housing developments and other factors, it is necessary to manage the demand for water in a way that will help in sustainable use of water in cities. A significant proportion of the water supplied to homes is used for irrigating lawn and garden areas (Maheshwari, Connellan 2005; Maheshwari 2012). There has been reasonable success in reducing the per capita indoor water use in Australia through various water conservation programs in the last ten years. However, our understanding of outdoor water use for irrigation is limited, particularly the effectiveness of irrigation practices employed by homeowners and opportunities that exist for water savings.

In general, there is a need to understand the most effective strategy to manage the water scarcity. For this, a clear understanding of the issues related to a number of questions is critical (Maheshwari 2006): How much water is being used for irrigation around homes? How much water is applied in excess of plant requirements? What opportunities are there to encourage improved irrigation efficiency? And what strategies can be implemented to make outdoor home irrigation more efficient and sustainable in the medium to long-term?

The specific objectives of the study were to: (i) examine the technical factors affecting the efficiency of outdoor irrigation around homes; (ii) obtain some baseline data on the working of existing home irrigation systems and the total irrigation water use and efficiency across different irrigation systems, and (iii) identify suitable strategies that will assist in conserving water use for outdoor irrigation.

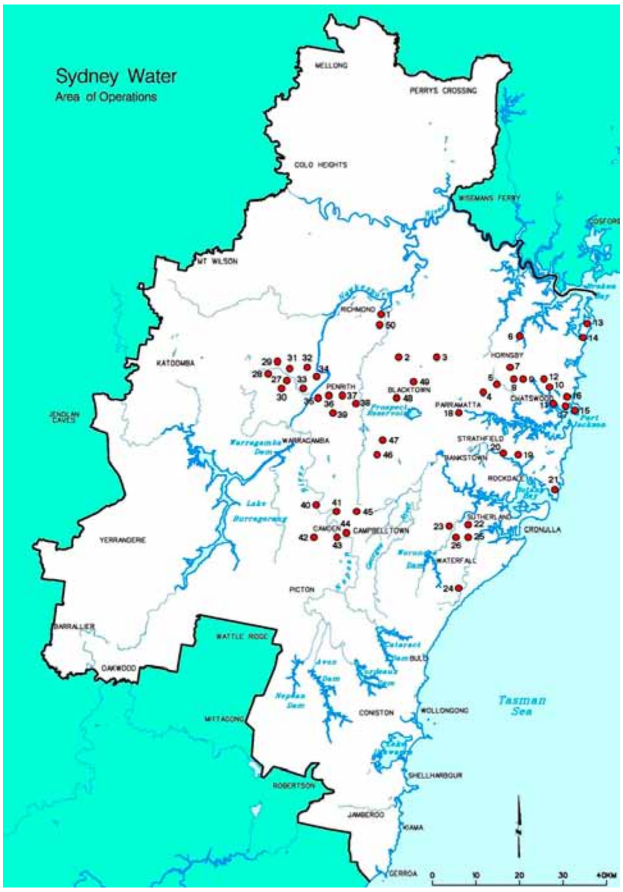

Fig. 1. Location of trial sites in the Sydney Metropolitan Area

1. Data collection

1.1. Study area

The study area is located in the Sydney Metropolitan area (SMA) in New South Wales in Australia (Fig. 1). From an irrigation point of view, the area includes a significant variation in soil types and climatic conditions. The soil texture ranges from sand and sandy loam to loam and clay loam (Pile 2000). The analysis of long-term climate data from the Bureau of Meteorology (BOM 2016) indicate that the average annual rainfall varies from 900–1400 mm and the mean minimum temperature varies from 2–8 °C and mean maximum temperature from 26–29 °C.

1.2. Site selection

Three factors that were considered important while selecting the trial home sites in the study area are: (i) climate, (ii) soil types and (iii) irrigation systems in use. It was decided to select the sites in such a way that they provided a good mix and representation of the major climatic zones, soil types and irrigation systems used by homeowners in the SMA. Considering the resources available and other constraints it was decided to select a total of 50 trial sites for the study.

An e-mail outlining the summary of the project and a call for expressions of interest to homeowners to participate in the study was circulated within the University of Western Sydney (UWS) staff network (>5000 employees). Forty-two responses were received from people wishing to have their home sites included in the study. Furthermore, Irrigation Australia Limited supplied a list of 11 homeowners who had irrigation systems with controllers professionally installed at their homes.

In order to include trial sites from other areas of the Sydney region, the Office of Western Sydney (OWS) and Western Sydney Office of Regional Councils (WSROC) were contacted. An e-mail announcement similar to the one used for the UWS staff network was sent out to all the councils in the Sydney region through OWS and WSROC. The email resulted in another 37 expressions of interest which provided a good coverage of potential sites, from medium to high rainfall areas.

All the homeowners who expressed interest to participate in the study were asked to fill out a fact sheet containing information about their irrigation systems, plants irrigated and irrigation practices they employ and a "mud map" of their property showing different irrigation areas. This information was used to ascertain the suitability of the sites for the study before formally including them. In total, 90 home sites were potentially available for inclusion in the study. The following criteria were used for selecting the required 50 home sites in the study:

- Type of irrigation system used to water the lawn and garden,
- Whether the irrigation system had a controller or not,
- Soil type,
- Climatic characteristics (particularly annual rainfall),
- Enthusiasm and support of the homeowner to participate in the study,
- Accessibility to the site, particularly the backyard,
- Travel time to visit the site to download the water meter data, and
- Risk of vandalism with meters and dataloggers.
- Other factors in the selection of sites included socio-economic aspects, linguistic and ethnic backgrounds of the homeowners, size of property and types of plants irrigated.

1.3. Setting up home sites and monitoring

The next phase of the project involved visiting the trial sites and installing water meters to outdoor taps. A total of five meters were selected randomly to test in the laboratory for calibration. Each meter was fitted with a Geosignal™ datalogger. Some sites with automatic irrigation systems required plumbers to install the meters. A crucial element of installing the water meters was ensuring they were fitted to the correct taps. This required direct communication with the owners to identify taps used for irrigating their gardens and lawns.

Site visits were made, approximately at monthly intervals, to each home site to download the information recorded by the dataloggers. With 50 home sites to be visited spread over a 40 km radius across the SMA an efficient travel route was established by clustering sites into five groups. Depending upon distances travelled, seven to nine sites were visited in any one day and the downloading at all 50 sites took five to seven full working days.

A personalised folder with appropriate data sheets was developed for each site and given to the homeowners during the first downloading session. Each folder included an introductory letter and three separate data sheets for collecting key information from homeowners about their irrigation systems and practices. In particular the data sheets required homeowners to provide information on (i) irrigation zones and spaces at the property, (ii) a record of irrigation times and (iii) homeowners' comments.

The data recording by homeowners was an important component of the study, not only to obtain essential information but also to make them active participants in the study. In general, the folders proved to be quite effective for most homeowners to record data consistently and reliably.

In addition to information obtained from dataloggers during each site visit, readings were noted manually for existing water meters installed by Sydney Water Corporation and for the meters specially installed to the back and front tap at each site. These water meter readings provided the total water used at each property, as well as that used for indoor and outdoor purposes separately, between the two consecutive download visits.

Data Analysis

The key data collected through site monitoring during the study included the date, time and volume of water applied for each irrigation event at all 50 sites. Other important data collected included the type of plants irrigated and areas of individual irrigated spaces. For the irrigation system audit, the data collected included irrigation system type and controllers, detailed description of the site's irrigation practice and system faults and any maintenance issues. The data collected are used to understand the following aspects at the sites:

- Outdoor water use – back and front of the home (kL),
- Percentage of the total water use for irrigation,
- Water used for irrigation of lawn vs. other parts of outdoor areas (kL and kL/100 m^2),
- Comparison of water use (kL/100 m^2) by different systems and their effectiveness,
- Analysis of watering habits of people (day of the week and the time of irrigation), and
- Overall effectiveness of irrigation systems at the sites.

The key parameters calculated from the monitored data included effective rainfall, evapotranspiration, irrigation interval, irrigation depth and irrigation index. The overall water balance was also performed to understand water use characteristics of the study area.

1.4. Weather

The weather data for the home sites were obtained from the Bureau of Meteorology (BOM 2016). The home sites were assigned weather stations that were located closest to the site. The seven weather stations selected for the study were Richmond, Penrith, Parramatta, Liverpool, Camden, Lane Cove and Sydney Airport. The key weather data of significance for the present study were daily rainfall and pan evaporation which were used to calculate the effective rainfall and actual evapotranspiration for the various trial sites.

1.5. Effective rainfall

From an irrigation point of view, effective rainfall is important since this determines the rainfall amount that infiltrates and is stored in the root zone and is available to plants for their water demand. As a rule of thumb, the evaporation from an exposed soil surface is about one-third of pan evaporation value (Matthias *et al.* 1986; NSW DPI 2015). This means any rainfall amount on a daily basis less than one-third of the evaporation value will not be available for plant use. In addition, depending upon the soil moisture content and the amount and intensity of rainfall, some proportion of rainfall may be lost from the area in the form of runoff and may not be effective to contribute to the plant water needs. Also, any light rain (a few mm) event is usually not effective due to its evaporation before it reaches the plant root zone and gets stored for plant use.

The computation of effective rainfall is quite complex as its estimation will depend on soil infiltration characteristics, soil moisture, prevailing weather conditions (temperature, radiation, wind velocity and humidity), intensity and quantity of rainfall, topography and other factors. The estimation of effective rainfall involves measuring rainfall amount, surface run-off, percolation beyond the root zone and the soil moisture uptake by plants. In fact, the effective rainfall estimation has been the subject of research and much debate for more than last 50 years, beginning with Thornthwaite in 1931 (Dastane 1974; Mohan *et al.* 1996; Obreza, Pitts 2002). There are a number of methods available for estimating effective rainfall (Cahoon *et al*. 1992). Considering the difficulties in monitoring field data and their variability, it is important to use a method that provides a reliable estimate and can be implemented with routinely available input data. Therefore, the estimation of effective rainfall in this study was based on the following equations:

$$R_e = 0 \text{ (for } R_d < 1/3\, E); \quad (1)$$

$$R_e = 0.5\, R_d \text{ (for } R_d \geq E), \quad (2)$$

where R_d – daily rainfall, mm; R_e – daily effective rainfall, mm; E – daily evaporation, mm.

The above equations are based on rules of thumb that the daily evaporation from exposed soil surface is about one-third of the daily pan evaporation and about 50% of the rainfall is effective if the daily rainfall is equal to or greater than the daily pan evaporation (Mueller-Dombois 1972; Matthias *et al.* 1986).

The advantage of the above approach is that it is simple and based on daily rainfall values and was found to be reliable when compared with a well-tested methodology proposed by Dastane (1974):

$$R_{em} = 0.8\, R_m - 25 \text{ for } R_m > 75 \text{ mm/month}; \quad (3)$$

$$R_{em} = 0.6\, R_m - 10 \text{ for } R_m > 75 \text{ mm/month}, \quad (4)$$

where R_{em} – monthly effective rainfall, mm and R_m monthly rainfall, mm.

The effective rainfall values estimated using Eqs (1) and (2) resulted in similar values when compared with those estimated using FAO method (Eqs (3) and (4)). The value of R^2 was quite high (0.94) and the coefficient of the regression equation was close to unity and the effective rainfall values estimated with the two methods were close to each other. Considering the spatial variability in rainfall and vegetation and soil type at home sites considered in the study, the method used for the estimation of effective rainfall is quite appropriate.

1.6. Evapotranspiration

The water use by plants, i.e., actual evapotranspiration (ET_a), depends on prevailing weather conditions, type of plant and the growth stage of the plant. One way to estimate ET_a is to first use the pan evaporation values for the area to estimate reference evapotranspiration (ET_r) and then convert ET_r to ET_a by using a crop coefficient:

$$ET_r = K_{pan} \cdot E_p; \quad (5)$$

$$ET_a = K_c \cdot ET_r, \quad (6)$$

where ET_a – reference evapotranspiration, mm; ET_r – actual evapotranspiration, mm; K_{pan} – pan factor (usually 0.8) and K_c – crop coefficient (varies with plant type and growth stage).

The average value of K_{pan} in this study was assumed 0.8 (Sakadevan *et al.* 2000). Similarly, the average value of K_c for maintaining a reasonable plant growth was assumed 0.5 for lawn, 0.9 for exotic plants in garden area and 0.5 native plants (Connellan 2013).

1.7. Irrigation events

Dataloggers were programmed to record information at 15-minute intervals and the raw data downloaded from the loggers contained date, time and flow volumes through front and back water meters. Since irrigation occurred for only a small period compared to the total time of data logging there were a large number of logged data with zero flows when there was no irrigation activity at the site. For computing the water use of each irrigation event, the dates and times when the flow volumes were greater than zero needed to be identified in a raw data file. A computer program was developed in Visual Basic™ to "clean up" the data recorded by the loggers and calculate the water volumes, times and durations for irrigation events at each site.

After the first download, due to very hot summer conditions (temperatures at times reaching >40 °C) during the January – February period of the study, dataloggers at some sites either failed to establish a connection with the computer or for some unknown reason started recording every five minutes instead of 15 minutes and ran out of their memory storage. This resulted in the need for a reliable estimation of missing data. In these circumstances the manual recordings of irrigation times that were kept by the homeowners became the primary source of information. Since the manual recordings included the date, time, duration and the zone of irrigation, average flow rate (L/min) was estimated from the previous downloaded data at the corresponding missing data site and was used along with the duration of irrigation to estimate the water volumes for irrigation events at the missing data sites.

Once the raw data files had been "cleaned up" and missing data had been estimated these files were then used to calculate relevant parameters to understand water use characteristics of the sites.

1.8. Irrigation interval and depth

The irrigation interval, i.e., the number of days between two consecutive irrigation events, can influence the total water use at a given site but it varies depending upon when homeowners decide to irrigate. Their decision to irrigate is often dictated by their convenience and the prevailing weather conditions. The interval is a useful indicator in comparing the effectiveness of irrigation systems and the total water use. In this study the interval was calculated for individual irrigation events and average values for different irrigation systems and zones at a given site.

The amount of irrigation can be expressed either as volume or depth of water applied. For the purpose of comparison of water applied in different irrigation zones and with different irrigation systems, the depth of water applied is preferred as it takes into account the area of irrigated space and so the depth of water applied is independent of the area irrigated.

In this study, the average depth of water application (mm) per irrigation event was calculated for each irrigation space at the site. Furthermore, to understand the variation of irrigation depth during the study period, the time considered for the calculation of average irrigation depth was based on month and entire period of the study. In addition, the depths calculated were examined to understand the influence of irrigation system, irrigation zone and soil-climatic zone of the sites.

1.9. Water use

Depending upon when the installation of water meters and dataloggers was completed, the duration of the study period varied slightly with sites. In order to understand the water use irrespective of monitoring duration at a given site, water use per unit time and area needs to be calculated. In this study, the water use expressed as kL/100 m^2/month (equivalent 1/10th of ML/ha/month) was calculated. Water use in kL/100 m^2/month is expected to provide a good indication of the effectiveness of irrigation practices at the site.

Irrigation index

Irrigation index provides insights into the effectiveness of irrigation practice (Connellan 2013). Irrigation index was calculated for the entire study period and was calculated for each irrigation zone at a given site. This enabled evaluation of the impact of irrigation systems, irrigation zones and soil-climatic zones on the effectiveness of irrigation practice.

One critical aspect of assessing the effectiveness of irrigation is to measure how much water is actually applied through both irrigation and rainfall when compared with what is actually required based on plant demand. Irrigation index is an indicator that can be used for this purpose to evaluate the effectiveness of irrigation practice or system at the site. The index in this study is defined as follows:

$$I_i = \frac{D_a}{D_r}, \quad (7)$$

where I_i – Irrigation index; D_a – Sum of irrigation depths applied and effective rainfall, mm and D_r – Estimated depth of irrigation required based on plant demand, mm.

The index is similar to the concept of efficiency but the emphasis here is to understand how much water is applied in excess of what is required by plants based on evapotranspiration demand. Therefore, the value of $I_i \leq 1$ for an irrigated area indicates little or no wastage of irrigation water, while $I_i > 1$ indicates wastage of water either due to percolation below root zone or surface runoff. The acceptable value of the index will depend upon the quality of lawn or garden desired. However, any value <1.0 will generally indicate a good irrigation practice or deficit irrigation and may influence the visual quality of landscape.

1.10. Water balance

Understanding water inputs in the landscape through rainfall and irrigation, how much of this water is used by plants and how much of this becomes runoff or percolates below plant root zone, is important in developing better irrigation practices and strategies. Water balance in the study was carried out based on the following equation:

$$I_v + R_e = ET_a, \quad (8)$$

where I_v – Irrigation depth applied (mm).

In Equation (8), it was assumed that the root zone in the study area is expected to be at or below field capacity due to continuing drought during the study period. This means the deep percolation of water below the root zone due to rainfall or irrigation will be negligible. Furthermore, runoff due to rainfall is accounted by effective rainfall in the water balance equation and there is negligible runoff due to irrigation.

Since there is a significant variation in plant type within given irrigation zones of lawn, garden (exotic plants and trees) and other garden (native plants and trees) irrigation systems and practices of individual homeowners and there was no control on how irrigation was done at individual sites it was not possible to perform water balance for individual irrigation events or sites. Instead the water balance was carried out based on all sites combined for individual irrigation zones (lawn, garden and other garden) and months.

2. Results

2.1. General

Key details of the field trial are given in Table 1 while the results of the study are summarised in Table 2. We observed that the key drivers motivating homeowners to participate in the study included their interest to save water and the environment, general interest in the study and a desire to learn about their water use and ways to conserve water and save on their water bill. A large number of spaces (72%) were irrigated with irrigation systems that did not have any controller. Irrigation systems with automatic controllers and tap timers each accounted for 15% of the total number of irrigated spaces.

The results reported here are based on monitoring over a five month period (November – March). This study was not a replicated experiment but a case study of 50 sites with homeowners irrigating as per their usual practice. It is unlikely that any two sites used in the study were similar in terms of the size of irrigated spaces, types of systems used or type of plants irrigated. The data reported provides a "snapshot" of the current irrigation practices and water use patterns at the home sites.

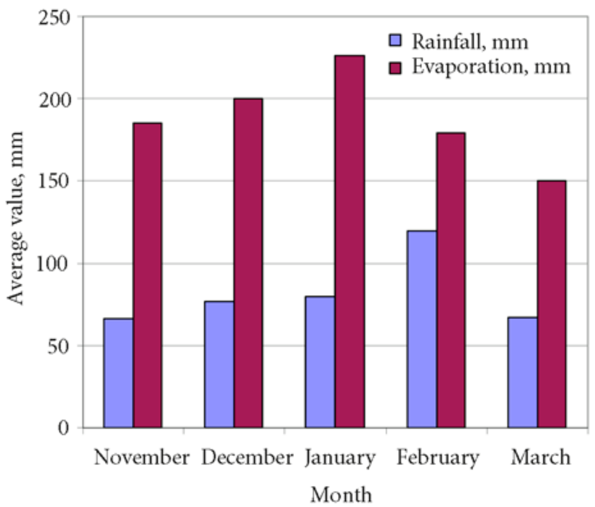

Fig. 2. Variation of rainfall and evaporation during the study period

2.2. Weather

The average monthly rainfall in the SMA, based on the seven weather stations considered in the study, varied from 67–119 mm/month and the average of the total over the five-month period was 411 mm (Fig. 2). The average monthly evaporation in the SMA varied from 179–226 mm/month and the average of the total over the five-month period was 940 mm. The average monthly effective rainfall in the SMA varied from 31–59 mm and the average of the total over the five-month period was 196 mm. Considering a pan factor of 0.8, the potential evapotranspiration over the study period is expected to be 750 mm. About half of the total rainfall in the study area was effective from the point of view of meeting the plant water needs. In addition, the rainfall during the study period satisfied about one-fourth of the potential evapotranspiration demand.

Table 1. Overview of the field trial

Item	Details
No. of sites	50
Irrigation zones at sites	Lawn, Garden and Other garden*
Average outdoor irrigated area per site	322 m^2
Total area under different irrigation zones	Total irrigated area – 16107 m^2 (1.6 ha); Lawn – 8167 m^2, Garden – 6681 m^2 and other garden 1260 m^2
Irrigation methods	Hand watering, drip, microjet, portable sprinkler and fixed sprinkler
Irrigation system controllers	No control, tap timer and fully automatic
Total number of irrigated spaces**	145
Average size of irrigated space	111 m^2
Total number of irrigation events monitored at the various sites during the study period	3456
Total volume of water used for irrigations at all sites during the study period	2013 kL

Notes: *Other garden zone includes native and mix of native and exotic plants.

**For example, a home site with a lawn in the front, a garden and lawn at the back will result in three irrigated spaces for the site.

Table 2. Summary of some key results from the study

Parameter	Value
Average irrigation water used per site as % of the total water use	34%
Average daily outdoor water use per site for irrigation	392 L/d
Average monthly outdoor water use per site for irrigation	12 kL/month
Average daily indoor water use per site	593 L/d
Average monthly indoor water use per site	18 kL/month
Average number of people per household	3.2
Water use for lawn as the % of the total irrigation water use	36%
Water use for garden as the % of the total irrigation water use	59%
Water use for other garden as the % of the total irrigation water use	5%
Area under lawn as the % of the total irrigated area	51%
Area under garden as the % of the total irrigated area	41%
Area under other garden as the % of the total irrigated area	8%
Area under hand watering as the % of the total irrigated area	23%
Area under drip system as the % of the total irrigated area	5%
Area under microjet system as the % of the total irrigated area	13%
Area under portable sprinkler as the % of the total irrigated area	31%
Area under fixed sprinkler as the % of the total irrigated area	28%
Average monthly water use per unit area for lawn	4.3 kL/100 m^2/month
Average monthly water use per unit area for garden	8.7 kL/100 m^2/month
Average monthly water use per unit area for other garden	4.7 kL/100 m^2/month

2.3. Description of trial sites

2.3.1. Irrigation systems

There were a total of 145 irrigated spaces spread over 50 home sites considered in the study (Table 1). Irrigation systems used at the sites included hand watering, drip, microjet, portable sprinkler and fixed sprinkler systems. Some homeowners have irrigation systems with controllers to assist in automating the start and stop of irrigation application at pre-determined schedules.

Out of 145 irrigation spaces spread over 50 sites, approximately one-third of them (35%) were irrigated by hand watering systems, one-fifth (23%) by portable sprinkler systems, one-fifth (22%) by microjet systems and the rest (19%) either by fixed sprinkler systems (11%) or drip systems (8%). This indicates that the hand watering system was the dominant irrigation system used by homeowners; the other popular systems were portable sprinkler or microjet systems. The use of fixed sprinklers or drip systems is still not widespread when compared with other systems.

2.3.2. Irrigation system control

Irrigation system control can play an important role in improving residential irrigation practice. In particular, it can help in preventing runoff from irrigated spaces especially when people forget to turn their irrigation system off after the application of required irrigation depth. The time and duration of irrigations at the sites in the study were controlled either manually using tap timers or fully automatic controllers. Over two-thirds of the total number of irrigated spaces had no controller and the rest in equal proportions were divided between tap-timers and automatic systems.

From an irrigation system point of view, out of all the spaces irrigated in the study, those irrigated using a hand watering system (about one-third of the total number of spaces) obviously had no controller. Most spaces irrigated with portable sprinkler systems generally also had no controller while those irrigated with fixed sprinkler system generally had a controller (often an automatic system). More than half of the total number of spaces irrigated with a microjet system had a controller but those irrigated with a drip system were mainly without a controller.

2.3.3. Plants irrigated

The outdoor areas comprise of lawns and gardens, however, some home sites irrigated plants and trees in pots in the front and back yards. The plants irrigated at the trial sites included grass for lawn, a range of exotic plants in garden areas, vegetable plants, native plants or a mixture of native and exotic plants. For the purpose of data analysis, the irrigated spaces at the various sites were grouped into three broad irrigation zones – lawn, garden and other garden.

The different types of lawns in the study area included kikuyu, buffalo and natural couch grasses. The garden zone includes exotic and vegetable plants, while other garden zone includes native or a mixture of native and exotic plants. The garden areas in small to medium sized houses often have exotic plants while the larger sized blocks mainly have native plants.

2.3.4. Areas irrigated

Over 90% of the sites are on medium (450–750 m^2) to large (>750 m^2) sized house blocks with relatively good sized lawn and garden areas. Out of the 50 home sites considered in the study, 27 are on sandy to sandy loam soil, nine on loamy soil and 14 on clay to heavy clay soil. Over half (60%) of the total number of irrigated spaces were associated with the garden zone, about one-third (30%) with lawn zone and the rest (10%) with other garden zone.

The total area of irrigated spaces at all 50 trial sites was 16,107 m^2 (1.6 ha) and the average outdoor area per site under irrigation was 322 m^2. Out of this, 51% of the total area was under lawn, 41% under garden and the rest under other garden. This means about half of the total area irrigated is under lawn zone and the other half is under garden and other garden zones. The areas irrigated using hand watering, portable sprinkler and fixed sprinkler systems are about the same (varied between 23% and 31%) while that under a drip system is the smallest (5%) followed by microjet (13%). Further examination of a number of spaces and the total area irrigated with different systems indicates that although hand watering is used for more spaces as compared with portable sprinkler systems, the total area irrigated with the portable sprinkler system is much larger.

The size of average irrigated space is 111 m^2, which is about one-third of the average size of outdoor area per site under irrigation (Table 1). The average size of irrigated space under fixed sprinkler was the largest (283 m^2), while that under portable sprinkler was half of the fixed sprinkler (148 m^2) and that under drip, microjet and hand watering was one-quarter (varied from 62–72 m^2). The data clearly indicates that the irrigated spaces with lawn tend to be larger compared to garden spaces and the larger lawn spaces are irrigated by fixed sprinkler systems.

Portable and fixed sprinkler systems cover more than half of the total area irrigated in the study whereas the hand watering system covers less than one-quarter of the area in spite of the latter being the most popular system with the homeowners. Portable and fixed sprinkler systems tend to be used on larger spaces. The drip system is not widely used and accounts for a very small percentage of the total area irrigated.

The total outdoor area for irrigation at a site can be categorised as very small (<50 m^2), small (50–100 m^2), medium (100–150 m^2), large (150–200 m^2) and very large (>200 m^2). It was observed that the size of the outdoor irrigated spaces was fairly spread across the very small, medium and very large categories. This suggests that any future water conservation strategies in the Sydney area need to be developed for the homes with those categories of outdoor areas in mind.

2.3.5. Influence of irrigated space size on water use

To understand the influence of irrigated space area on water use, average water use for a range of space areas was calculated. It was observed that homeowners tend to apply high volumes of water per unit area (kL/100 m^2/month) on smaller irrigated spaces (areas <50 m^2), as high as four times the water used per unit area on larger irrigated spaces. Also those homeowners who apply excessive water (kL/100 m^2/month) on smaller areas generally do not apply excessive volumes on larger spaces (if present). Further examination of the data indicates that most small areas belong to garden zone and those areas are mainly irrigated by hand watering or microjet system with no controller. Also the microjet systems on small areas are more likely to be a "do-it-yourself" (DIY) type system and not well designed.

The average water use during the study period for sites with very small irrigated areas was 23.2 kL/100 m^2/month and for very large irrigated areas was 5.2 kL/100 m^2/month. The water use in kL/100 m^2/month generally decreased with the size of the total irrigated area at the site. The water use for the sites with very small and small irrigated areas was up to four times than for the sites with larger areas. This means, homeowners with smaller irrigated areas tend to apply quite high volumes of water and in most cases they over irrigate their properties.

Although the total volume of water applied per irrigation event on very small and small irrigated spaces is relatively low, the water applied expressed as kL/100 m^2/month is too high and is most likely due to inefficient irrigation on those spaces. About one-fourth of the total number of irrigated spaces have areas <50 m^2 and if this is representative of the SMA there are significant opportunities to target smaller areas for water conservation strategies.

In general, for smaller irrigated spaces, this finding clearly indicates that the over-irrigation of smaller spaces is most likely related to the irrigation system (i.e., hand watering and microjet). Furthermore, homeowners are probably not able to estimate properly how much water they need to apply to replenish the root zone or they do not take the amount applied seriously as the quantities involved are relatively small due smaller areas.

2.3.6. Irrigation interval

The irrigation interval varied with irrigation system, irrigation zone and system control. In addition, it varied depending upon the prevailing weather conditions and the amount of rainfall received between two consecutive irrigations. On average, irrigation occurred every seven days in garden areas, nine days in lawn areas and 11 days in other garden areas). In regards to irrigation systems, irrigation is relatively more frequent with microjet systems and least frequent with drip systems. Also watering tends to be relatively more frequent on sites with automatic systems (particularly with microjet systems) than the sites where no controllers were used. On average, homeowners tended to water every eight days during the study period.

2.3.7. Irrigation volumes and depths

The volume of water used varied with irrigation systems and zones. The microjet system accounted for the largest volume (31% of the total water applied during the study), followed by portable sprinkler systems (26%) (Table 3). The drip system accounted for the least volume (6%). The data suggest that microjet systems need to be targeted for any future water conservation strategies due to its very large share of the total irrigation water usage.

The average depth per irrigation event was the highest for drip systems, followed by microjet systems and was the lowest for fixed sprinkler systems (Table 4). This indicates that the soil type and irrigation management practices can influence the depth applied, and so the drip method not necessarily always uses less water. The average depth of water application per irrigation event varied with the month and the type of system control and the study has clearly shown that irrigation systems with automatic controllers apply lower depth than those with tap timers or no controller (Fig. 3). The analysis of the water use data indicates the influence of irrigation methods on the irrigation depth applied. On average homeowners apply about 40% more water per irrigation to garden areas compared with lawn areas. The depth of water application per irrigation was lowest with fixed sprinkler systems and the highest with drip systems.

Figure 4 shows that average irrigation depth varied with changes in pan evaporation and effective rainfall values. The irrigation depth applied closely followed the trend in evaporation values and peaked when the evaporation peaked and the depth changed depending upon the values of effective rainfall. This indirectly indicates that generally homeowners tend to adjust the irrigation depth intuitively according to the prevailing weather conditions.

Table 3. Variation of water application with different irrigation systems during the trial period

Irrigation system	Total number of irrigation events	Volume of total irrigation water applied, kL	% of the total volume of irrigation water applied	Average of depth of water application per irrigation, mm
Hand watering	1145	368	18	9.8
Drip	214	126	6	12.2
Microjet	1093	633	31	11.3
Portable sprinkler	636	522	26	8.7
Fixed sprinkler	368	363	18	4.9

Table 4. Variation of average depth of water application per irrigation with irrigation systems and system controls

Irrigation system	Average depth of water application, mm			
	No controller	Tap timer	Auto-matic	Overall average
Hand watering	9.8			9.8
Drip	17.0	9.5		12.2
Microjet	20.1	22.2	7.1	11.3
Portable Sprinkler	9.7	6.0		8.7
Fixed Sprinkler	6.6	9.1	3.6	4.9
Overall average	11.1	11.4	6.2	9.7

Water balance analysis for the study period indicates that about half of the total irrigation water needed during the study period was met through rainfall. The average depth of irrigation water applied, after converting the depth on a daily basis (irrigation depth divided by irrigation interval), varied from 2.0–2.5 mm/d, while the average daily pan evaporation values varied from 5.4–7.7 mm/d.

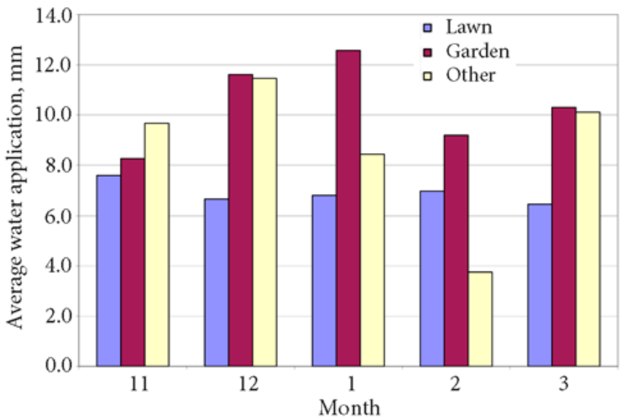

Fig. 3. Average depth of irrigation during different months (11 = November) for the various irrigation zones during the trial period

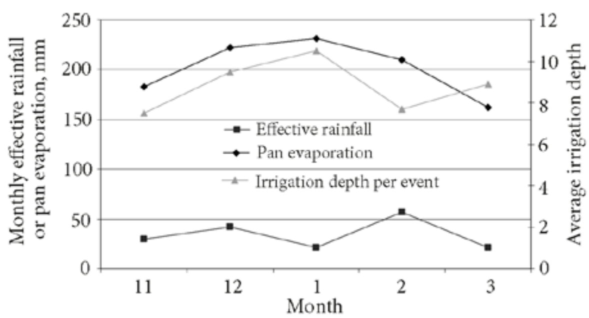

Fig. 4. Variation of the average pan evaporation, effective rainfall and irrigation depth values with month during the trial period

2.3.8. Outdoor and indoor water usage

The total outdoor and indoor water use for irrigation during the study period varied from one download period or month to the next and it varied considerably with one site to the next. The outdoor water use at a given site depends on the weather conditions, size of the irrigated area and frequency of irrigation, whereas the indoor water use depends mainly on the number of people living at the site. However, some fluctuation in the indoor water use, especially during the December – January period, may be attributed to the changes in the number of people at home.

The total water used at the sites during the study period (five months) varied from 20–258 kL with an average value of 106 kL per site. The total water used for outdoor during the study period varied from 2–214 kL with an average value of 43 kL per site. Outdoor water use as a percentage of total water used for individual home sites varied from 2–84% during the study period and indicated a large variation with sites. However, the average value for the outdoor water use for all 50 sites did not vary much – 37% during the December – January period, 35% during the January – February period and 31% during the February – March period. For the entire study period, the average outdoor water use was 34% (Table 2). The wide variation in the volume of outdoor irrigation water use with sites indicates that there is a considerable variation in the size of irrigated areas and irrigation practices. In particular, this demonstrates the need for well-designed educational programs to improve irrigation practices of individual homeowners.

The average daily water use for outdoor during the study period was 392 L/d with values varying between 21–2057 L/d. On a monthly basis, the average water use per site is about 12 kL per month for the study period. The variations in outdoor water use indicates that some sites were using negligible or low volumes of water due to irrigating only occasionally or had a small outdoor area for irrigation, while the other sites had a quite high water consumption due to large outdoor irrigated areas.

The average value of daily water use for outdoor also varied from one download period to the next (253–488 L/d) or from one month to the next (Table 5), and this variation is mainly attributed to changes in evapotranspiration demand and rainfall received.

A total of 2013 kL water was applied at the various sites over the study period (Table 5). Out of this, about two-thirds of the total irrigation water was applied in the garden and other garden zones (59% for garden zone +5% for other garden zone) and one-third in the lawn zone (36%). This indicates that, on average, garden and other garden areas account for two-thirds of the total irrigation water used although they represent half of the total area irrigated at the various sites. This indirectly indicates the differences in water requirements and effectiveness of irrigation practices of these zones. Furthermore, the study demonstrates that garden zones were observed to be a very high water user per unit area.

The number of people living at the site varied from one to six with an average value of 3.2 persons per household. The average daily per capita indoor water use during the study period was 201 L/d/person. The average indoor daily water use per site during different download periods varied from 577–685 L/d and the average value for the study period was 593 L/d). When compared with the outdoor daily water use the average daily indoor daily water use did not vary so widely with download periods.

2.3.9. Variation in water use with month

The water used at the sites varied from one month to the next depending upon the rainfall and evaporation (Table 6). It varied from 2.6–5.0 kL/100 m^2/month for lawn, 6.9–10 kL/100 m^2/month for garden and 1.7–8.2 kL/100 m^2/month for other garden. On the other hand, for all the irrigation zones combined, the variation of water use with month was fairly constant (varied from 5.9–7.5 kL/100 m^2/month). In general, there is no clear trend in the water use with month although the variations in rainfall and evaporative demands during the study period may have contributed to the changes in water use.

The average value of water used, based on all 50 sites over the study period, was 6.8 kL/100m^2/month. The average values of water used for the lawn and other garden areas were similar (4.3 for lawn and 4.7 kL/100 m^2/month for other garden) but for the garden areas the average value (8.7) was about twice that for the lawn areas. The study suggests that the garden areas account for a significantly high water usage per unit area and are probably being over-irrigated by homeowners.

Table 5. Variation of the total volume of water applied with irrigation systems and zone during the trial period

Irrigation method	Volume of water applied, kL			
	Garden	Lawn	Other Garden	Total
Drip	125	0	2	126
Fixed Sprinkler	62	302	0	363
Hand watering	287	46	35	368
Microjet	557	15	60	633
Portable Sprinkler	156	366	0	522
Total	1187	729	97	2013
% of the total	59	36	5	100

Table 6. Variation of water use with system, system control and irrigation zone

Irrigation system	Irrigation zone	System control and water use (kL/100 m²/month)		
		No controller	Tap timer	Automatic
Drip	Garden	5.0	6.1	
	Other garden	2.1		
Fixed sprinkler	Garden	2.3		2.3
	Lawn	5.4	6.2	1.7
Hand watering	Garden	5.0		
	Lawn	2.1		
	Other garden	2.3		
Microjet	Garden	10.2	5.3	11.0
	Lawn		9.2	
	Other garden	1.9		8.6
Portable sprinkler	Garden	1.8		
	Lawn	2.5	3.3	

Effects of irrigation systems on water use and efficiency

Table 6 shows that two out of three sites have their water use <10 kL/100 m^2/month, about one in five sites have their water use in the range of 10–20 kL/100 m^2/month and one in seven sites have >20 kL/100 m^2/month. Considering the pan evaporation and effective rainfall values for the study area, any irrigation application >10 kL/100 m^2/month most likely indicates over-irrigation. The water use data in kL/100 m^2/month show that one-third of sites considered in the study are over-irrigated and in some cases the water applied is two or more times the water actually required by plants.

It is interesting to note that more than half of the water was applied with microjet and portable sprinkler systems (31% with microjet + 26% with portable sprinkler). The water applied with a drip system was small (6%) while water applied with hand watering and sprinkler systems was medium (18% each). This indirectly suggests that microjet systems need to be considered seriously in any future water conservation strategies for outdoor water use.

To understand the influence of the irrigation system on efficiency of water application, water use values in kL/100 m^2/month were calculated for different irrigation systems, irrigation zones and system control. The data indicates that water use is significantly influenced by the irrigation system and its control. The hand watering, drip and microjet systems use more water than fixed sprinkler and portable sprinkler systems. In addition, the water use of fixed sprinkler systems with an automatic controller for lawn irrigation was comparable to that for hand watering of lawns. One reason for the lower water use may be related to the fact that, in most cases, the systems with an automatic controller used in this study were professionally designed and operated late at night or early in the morning, resulting in reduced evaporation losses and increased application efficiency. However, the microjet system was observed to be the highest water user and probably the most inefficient system irrespective of system control.

2.3.10. Irrigation index

Irrigation index in this study varied considerably with the system used at the site (Table 7). The average value of the index for hand watering was <1 for all three irrigation zones (i.e., lawn, garden and other garden) indicating that generally there was no over-irrigation with the method. However, this does not necessarily mean that the water was applied uniformly over the entire area with the hand watering system.

The value of the index for drip system was 0.71 for garden zone but was 2.1 for other garden zones. It should be noted that the index value for other garden zone was drip system at one site only and as such the value should be treated with caution. However, this indicates that there was generally no over-irrigation with drip system for garden zones but there is a possibility of water wastage if the system is not used properly.

Fixed sprinklers had the average value of the index >1 for lawn zones but <1 for the garden zone. Further examination of data indicate that the value of index was >1 for sites where there was no controller used. This clearly demonstrates the importance of system control in improving irrigation practice.

Further examination of irrigation index values indicates that 54 out of 145 irrigated spaces had index values >1 and 18 had values >1.5. This means over one-third of irrigated spaces in the study were over-irrigated. Further the water use as kL/100 m^2/month for individual sites varied between 0.04 and 70 with an average value of 11. For 70% of sites the water use was <10 kL/100 m^2/month and three sites included in the study had a distinctly high water use (>20 kL/100 m^2/month). Further examination of data indicates that the sites with higher water use were the ones with irrigation index >1, probably indicating considerable wastage of water at those sites. This again indicates that water use and irrigation index can vary considerably with sites depending upon the irrigation practice of homeowners and the frequency of irrigation.

Examination of data in Table 7 indicates that homeowners tend to consistently over-irrigate with microjet systems. Overall, the microjet system was the most inefficient system of irrigation among the systems included in the study. The value of the index was >1, irrespective of irrigation zone and system control used. The inefficiency of microjet systems is probably related to factors such as homeowners using DIY ("do-it-yourself") design and installation of the system, small areas being irrigated and too many microjets per unit area being used, thus leading to over-irrigation.

2.3.11. Watering habits of people

By recording the time and day of watering, it was possible to develop an understanding of when homeowners tend to irrigate if there are no restrictions. Over one-third (37%) of the total irrigation events occurred between 3 pm and 9 pm, however a significant proportion of events (18%) occurred between 9 am and 3 pm when evaporation losses are expected to be excessive (Fig. 5). A significant proportion (18%) of events occurred between 6 am and 9am and about a one-quarter between late night and early morning, most of them at sites where automatic irrigation systems have been installed.

Table 7. Variation of average irrigation index with irrigation systems and irrigation zones

Irrigation system	Average irrigation index		
	Lawn	Garden	Other Garden
Hand watering	0.92	0.89	0.82
Drip	–	0.71	2.06
Microjet	1.14	1.20	1.34
Portable sprinkler	0.90	0.83	1.09
Fixed sprinkler	1.10	0.79	–

3. Discussion

Hand watering was the most used irrigation method in the study with 40 out of the 114 spaces in this study being irrigated this way. On average hand watering was the most efficient watering method across lawn, garden and other garden. Furthermore, the study clearly demonstrated that, for irrigating lawns, hand watering method, portable sprinkler systems and fixed sprinkler irrigation systems with automatic controllers used similar volumes of water per unit area basis over the duration of the study. Interestingly, the study indicated that hand watering and portable sprinklers resulted in higher water application efficiency and fixed sprinkler systems with automatic controllers generally applied too little water too often. Microjet irrigation was observed to be the most inefficient of the irrigation systems examined in this study.

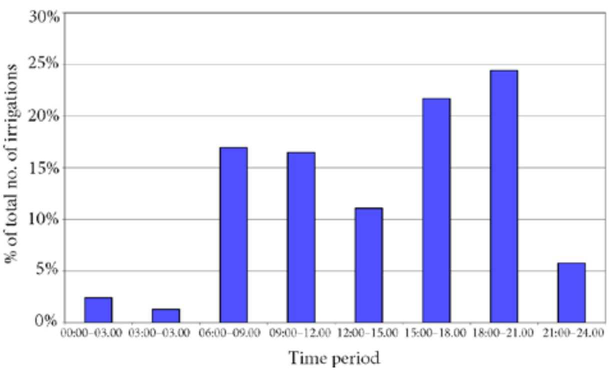

Fig. 5. Percentage of total number of irrigation at different times during the trial period

About one in five irrigation events occurred during the period between 9 am and 3 pm, the time of highest potential evaporation losses. Stopping irrigation during these hours would result in further water savings. Also, new irrigation technologies can help achieve water savings and improve the irrigation index. For example, irrigation systems with soil moisture sensors have been reported to increase water savings during wet weather conditions and overall can maintain acceptable lawn quality (Cardenas-Lailhacar *et al.* 2008).

Relatively few irrigated spaces (17 out of 114) had systems that were equipped with automatic controllers. The majority of automatic controllers used (11) were for irrigated spaces with microjet systems and the remaining (6) were for irrigated lawns spaces with fixed sprinkler system. There was a large variation in the volume of water applied by these systems, with microjet applying the most water and fixed sprinkler lawns applying the least amount of water on a per unit area basis. A number of studies have demonstrated significant water saving benefits of using controllers such as automatic timer, automatic timer with rain sensor, automatic timer with soil-water sensor and evapotranspiration controller for irrigation scheduling (Al-Ajlouni *et al.* 2012; Dobbs *et al.* 2014; Davis, Dukes 2014; Haley, Dukes 2011; McCready, Dukes 2011).

The study found that most homeowners have poor or limited understanding of plant water needs and that, in at least one-third of the sites, up to twice the estimated plant water requirement was applied. The monitoring in this study clearly suggests that irrigation scheduling plays an important role in the total water used for irrigation. A study in Florida, USA showed that more than half of the homeowners over-irrigated to some extent (Romero, Dukes 2014). Haley *et al.* (2007) also observed that substantial over-irrigation can occur where homeowners scheduled irrigation occurs without them clearly understanding irrigation requirements. They suggested that scheduling could be improved by using soil moisture sensors for irrigation control and where possible by using some form of real time or near real time weather data to schedule irrigations.

In an earlier study of 397 homes in Perth, Western Australia, Syme *et al.* (2004) observed that external water use of homes was higher for homes that used automatic controllers. The higher water use for the systems with automatic controllers in their study was attributed to improper irrigation scheduling practices followed by homeowners. As highlighted in Table 6, the water use not only depends on the system of irrigation but also on whether a controller is used, the design and maintenance of the irrigation system and irrigation skills (e.g., correct estimation of water requirement) of homeowners. Therefore, it will be vital for the water supply authorities to initiate well targeted educational programs to make sure that the systems are used properly to attain water savings.

The water use and irrigation system uniformity is often affected by low pressure in the irrigation system and the use of incorrect sprinkler spacing in design and installation (Baum *et al.* 2003). Non-uniformity of irrigation can cause uneven grass growth, particularly on the edges of a residential home site and can result in the homeowners increasing irrigation volume to that area. Furthermore, not all types and brands of sprinkler heads are the same in terms of their irrigation performance. For example, rotary sprinkler heads create more uniform distributions than fixed spray heads (Baum *et al.* 2005). Therefore, a properly designed irrigation system is important for achieving water savings and higher irrigation uniformity distribution.

Water restrictions during drought periods in Australia are based on aspects such as restricting the use of sprinkler systems and irrigating on certain days and at certain times of the day. The analysis of Brennan *et al.* (2007) indicated that as the water restrictions on sprinkler use becomes more restrictive, water savings occur up to a point by substituting hand-watering method for sprinkler method. Beyond this point, making irrigation restricted to hand-watering results in reduced leisure time for homeowners. A study in the United States indicated that when the once-a-week water usage restriction was introduced, homeowners tended to apply more water to avoid any shortage of water for their lawns and probably resulted in lower irrigation efficiency (Ozan, Alsharif 2013).

Syme *et al.* (2004) have argued that households that derive the significant personal benefits from their gardening activities are the ones use more water. The association between quality of life and outdoor water use needs to be carefully examined if water policies in the context of demand management, supply reliability and water use restrictions are to reflect community aspirations and values. Furthermore, from a demand management point of view, this suggests that garden areas need to be specifically targeted for educating homeowners to improve their irrigation practice and introducing or promoting smart irrigation technologies in garden zones (Harlan *et al.* 2009). Another aspect that may need to be targeted is to audit irrigation systems used around homes to evaluate their effectiveness and identify irrigation system faults and issues that impact on the effectiveness of outdoor home watering (Maheshwari 2012). In general, the findings of this study highlight some major challenges to the development of effective water conservation in the residential irrigation sector. It appears that control of the irrigation systems is more important in limiting irrigation duration and avoiding irrigation at inappropriate times.

Conclusions

The study provides some valuable insights into the characteristics of irrigation practices and their effectiveness and it highlights some significant opportunities to conserve water in the residential sector. The key conclusions and recommendations for outdoor water conservation are as follow:

- On average garden areas account for two-thirds of the total irrigation water use but represent only half of the total area irrigated at the various sites. From a demand management point of view this suggests that garden areas are the substantial water users and need to be especially targeted for educating homeowners to improve their irrigation practice and introducing or promoting smart irrigation technologies.
- The values of irrigation index and water use in kL/m^2/month for the various irrigated spaces highlight that the effectiveness of irrigation not only depends on the type of irrigation system used but also on whether a controller is used, the design and maintenance of irrigation system and homeowners' irrigation skills (e.g., correct estimation of water requirement and seasonal adjustment of irrigation frequency). In particular, all properly designed and maintained irrigation systems have the potential to save water when matched with an appropriately scheduled and maintained irrigation controller.
- Outdoor water use as a percentage of the total water use for individual home sites varied from 2–84% during the study period and indicated a large variation with sites. This wide variation, although related to the size of irrigated areas, was influenced by the irrigation practices of homeowners. This demonstrates the importance of developing a range of water conservation measures that are tailored to an individual homeowner's irrigation activity.
- Homeowners tend to over irrigate smaller areas (areas <50 m^2) as much as four times the water used per unit area on larger irrigated areas. Most small areas belong to garden beds and are mainly irrigated by hand watering or microjet systems with no controller. The over irrigation of smaller areas is most likely related to the irrigation system used and skills of irrigators. Significant opportunities exist for water conservation through appropriately designed educational programs and the installation of improved irrigation systems for smaller areas.

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