A Framework for Development and Evaluation of Policies and Programs for Urban Irrigation Demand Management

by

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Dedication

I dedicate this thesis to my sister Dr. Rukminidevi K. Shastri (Maiden name: Dr. Meena P. Thuse) and her husband Dr. Acharya K. Shastri. It is only for you and because of you that I started on this journey, stayed on it and completed it. Thank you for your inspiration, strength and support throughout.
Declaration of Originality

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text.

The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution.

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Bhakti Lata Devi

January 2009
Abstract

Water resources around the world are under increasing pressure from growing populations and the matching demand for food. Climate change is making its presence felt through trends to decreased rainfall and increased temperatures and evaporation rates, resulting in longer and more frequent spells of dry weather. Urban areas are competing more strongly with irrigated agriculture, industry and the environment for a share of the water supply. Urban water demand management has thus come into sharper focus as an integral part of any sustainable water management strategy.

Urban irrigation, the watering of lawns and garden beds in the residential sector and irrigation of public open spaces like sporting grounds and parks, forms a significant component of urban water demand. Irrigation demand provides, in theory, more scope and opportunities for demand reduction and water use efficiency than indoor water demand, but in practice indoor demand has received greater levels of attention and investment from urban water service providers. This is because urban irrigation demand and its water saving potential, influenced by a complex set of climatic, biophysical, technological and behavioural factors, are relatively more difficult to analyse and predict. A random approach to the development of outdoor demand management programs, the lack of evaluation of such programs where they exist, and reliance on mandatory water restrictions for achieving reductions in demand, are symptoms of the problem.

The thesis seeks to address the problem by proposing a modelling framework based around the concepts of *landscape irrigation budget* and *water saving potential*, and argues that the proposed framework provides a rational and systematic approach to development of demand management policies and programs for urban irrigation through its capacity to: (a) develop irrigation benchmarks and budgets for different urban landscape types located in different soil–climate zones; and (b) evaluate the effectiveness of demand management programs and policies.

The thesis explores this proposition by applying the proposed concepts and framework to a selection of domestic gardens attached to single detached dwellings located in the local government areas of Kogarah and Penrith, representing two
different soil–climate zones within the Greater Sydney Metropolitan area of New South Wales, Australia. The research methodology integrates the following: (a) a survey of domestic gardens, using aerial photographs, to characterise them with respect to their area, water use and microclimate characteristics; (b) building a conceptual biophysical model using a rational approach to estimate landscape irrigation budget for those gardens; (c) estimating irrigation budgets for gardens in the two areas; (d) water demand modelling using historical metered water consumption data (for a period when there were no water restrictions) to estimate the water saving potential of those gardens; and (e) analysis of historical metered consumption data (for a period when water restrictions were imposed) to evaluate the effectiveness of restrictions as urban irrigation demand management policy.

The proposed concepts and modelling framework incorporate a well-defined and measurable indicator (landscape irrigation budget) and a monitoring and evaluation framework (water saving potential), both of which are crucial to facilitating sustainable management of any natural resource. In addition, the modelling framework developed in the thesis is simple, transparent, adaptable and flexible, the characteristics that make a decision-making model effective.

**Keywords**

Outdoor demand, demand management, sustainable irrigation, urban irrigation, domestic gardens, urban landscape, public open space, water policy.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AD</td>
<td>Allowable Depletion</td>
</tr>
<tr>
<td>ASW</td>
<td>Available Soil Water</td>
</tr>
<tr>
<td>AWWARF</td>
<td>American Water Works Association Research Foundation</td>
</tr>
<tr>
<td>CBD</td>
<td>Central Business District</td>
</tr>
<tr>
<td>CF</td>
<td>Crop Factor</td>
</tr>
<tr>
<td>CWD</td>
<td>Cumulative (Soil) Water Deficit</td>
</tr>
<tr>
<td>ET</td>
<td>Evapo-transpiration</td>
</tr>
<tr>
<td>ETc</td>
<td>Crop Evapo-transpiration</td>
</tr>
<tr>
<td>ETo</td>
<td>Reference Evapo-transpiration</td>
</tr>
<tr>
<td>EUA</td>
<td>End-Use Analysis</td>
</tr>
<tr>
<td>FAO</td>
<td>Food &amp; Agriculture Organization</td>
</tr>
<tr>
<td>FC</td>
<td>Field Capacity</td>
</tr>
<tr>
<td>FY</td>
<td>Financial Year</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>HWaSP</td>
<td>High Water Saving Potential</td>
</tr>
<tr>
<td>HWU</td>
<td>High Water Using</td>
</tr>
<tr>
<td>LET</td>
<td>Landscape Evapo-transpiration</td>
</tr>
<tr>
<td>LGA</td>
<td>Local Government Agency</td>
</tr>
<tr>
<td>LWaSP</td>
<td>Low Water Saving Potential</td>
</tr>
<tr>
<td>LWR</td>
<td>Landscape (Irrigation) Water Requirement</td>
</tr>
<tr>
<td>LWU</td>
<td>Low Water Using</td>
</tr>
<tr>
<td>MAD</td>
<td>Maximum Allowable Depletion</td>
</tr>
<tr>
<td>MLIB</td>
<td>Monthly Landscape Irrigation Budget</td>
</tr>
<tr>
<td>MWaSP</td>
<td>Moderate Water Saving Potential</td>
</tr>
<tr>
<td>MWU</td>
<td>Moderate Water Using</td>
</tr>
<tr>
<td>NLWR</td>
<td>Non Limiting Water Range</td>
</tr>
<tr>
<td>NWaSP</td>
<td>No Water Saving Potential</td>
</tr>
<tr>
<td>PAWC</td>
<td>Potential Available Water Content</td>
</tr>
<tr>
<td>PWP</td>
<td>Permanent Wilting Point</td>
</tr>
<tr>
<td>RAW</td>
<td>Readily Available (Soil) Water</td>
</tr>
<tr>
<td>RZ</td>
<td>(Effective) Root Zone</td>
</tr>
<tr>
<td>SDD</td>
<td>Single Detached Dwelling</td>
</tr>
<tr>
<td>SWC</td>
<td>Sydney Water Corporation</td>
</tr>
<tr>
<td>TQVSI</td>
<td>Turf Quality Visual Standard Index</td>
</tr>
<tr>
<td>WASP</td>
<td>Policy framework</td>
</tr>
<tr>
<td>WASP Framework</td>
<td>Rational method proposed in the thesis</td>
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<tr>
<td>WASP Method</td>
<td>Landscape irrigation water requirement</td>
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<tr>
<td>WaSP</td>
<td>Water Saving Potential (of landscape)</td>
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<td>WUCOLS</td>
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1. Introduction and Literature Review

1.1 Introduction

Water resources around the world are under increasing pressure from a growing population, and the increased demand for food to support that growth (Gleick 2000). The increasing variability in weather patterns attributed to climate change has impacted on water supplies, with longer spells of dry weather and drought (Vorosmarty et al. 2000). Urban areas have to compete harder with irrigated agriculture, industry and the environment for their share of water supplies. Hence, urban water demand management has come into sharp focus as an integral part of sustainable water use and management policy and strategy (Roberts 2005, Mitchell et al. 2004).

Urban irrigation refers to the application of water to urban green space. Urban green space includes privately owned and maintained domestic gardens and ornamental landscapes on commercial, institutional and industrial properties as well as publicly owned recreational parks, sporting fields, golf courses and other such open spaces (Tzoulas et al. 2007). It forms a significant component of water demand in most urban regions of Australia (Loh and Coghlan 2003; Barton and Argue 2005; Roberts 2005). Urban water utilities across Australia resort to a policy of restricting water application on all urban green spaces during periods of drought when the supply levels start to drop (Brennan et al. 2007). While the policy of water restriction may succeed in conserving water resources, it does so at the cost of the quantity and quality of the urban landscape, namely the lawns, gardens, parks and sporting fields which are maintained by urban irrigation and of the social, economic and environmental benefits associated with it (Dandy 1992; Brennan et al. 2007; Fam et al. 2008). However, in the absence of any tool or framework that has the capacity to analyse existing urban irrigation demand and determine the demand management potential of various categories of urban landscapes, restrictions on water use remains the preferred policy option for obtaining tangible water savings by water utilities in urban regions of Australia, North America and most parts of developed and developing world.
Investment in the development and implementation of water conservation and demand management programs is cost intensive (SWC 2007; Baumann 1998). For example, since 1999 the Sydney Water Corporation (SWC) has invested more than $140 million in operating and capital expenditure on such initiatives (SWC 2007). Like any other business decision, the investment in demand management is based on prediction and quantification of the return on the investment, in terms of the volume of water savings that can be provided by the program (Turner et al. 2004; White and Fane 2002). Urban water utilities have therefore developed tools for analysing the indoor water demand of the population that they serve that allow them to quantify the baseline demand for water by each residential end-use (e.g. toilets, shower, dishwasher, washing machine) (Baumann et al. 1998). Demand analysis tools are also used to estimate and quantify the water saving potential that exists with each end-use (Turner et al. 2004). Knowing the volume of water that can potentially be saved through implementing a program provides the confidence necessary for investment in a policy or program that seeks to save potable water and/or reduce water demand.

However, such a tool is currently unavailable for analysing outdoor (urban irrigation) demand (White et al 2004). Absence of such a tool results in lack of confidence in investing into any long-term programs to target reduction in urban irrigation demand, or outdoor demand as it is commonly recognised by urban water planners. Hence, to achieve tangible water savings the utilities prefer to take the regulatory approach by enforcing restrictions on the irrigation of gardens and lawns over the non-regulatory approach of implementing a demand-management program (Brennan 2007). However, historical annual water consumption charts of urban water systems show that water demand returns to previous levels when water restrictions are lifted (SWC 2007), thus revealing the short-term and unsustainable nature of the water savings that result from such restrictions.

The irrigation demands of gardens and public open spaces are more difficult to analyse than indoor water demands. This is because, unlike indoor demand, urban irrigation demand depends on a complex set of factors. Apart from being dependent on the technical efficiency of watering devices, and on human behavioural factors, urban irrigation demand is a function of biophysical factors such as water–atmosphere–soil–plant interactions which, in turn, are dictated by climatic factors...
(e.g. rainfall, evaporation, wind speed, humidity, radiation) together with the varying characteristics of soils and plants (Costello et al. 2000). Any attempt to elucidate urban irrigation demand should therefore integrate modelling of the biophysical water–atmosphere–soil–plant interactions into the analysis. Such integration would allow for the incorporation of science into the analysis, thus taking out the uncertainty.

To put the management of urban irrigation demand management into perspective, the difference between micro-management of individual irrigation sites and macro-management of aggregate urban irrigation demand at regional or suburban level needs to be elucidated. Micro-management of irrigation entails managing the frequency and amount of irrigation of individual sites, on a specific time basis (e.g. hourly, daily). Whereas macro-management of urban irrigation demand implies management of aggregate water demand of urban landscapes through promotion and facilitation of water-use efficiency, use of alternative water sources and behavioural change among urban irrigators. This could best be achieved through implementation of well-informed and well-targeted policies and programs.

In recent years, various tools, gadgets and calculators have been trialled by urban water utilities in Australia for the purpose of scheduling irrigation on urban landscapes such as public open space. Presentations at the Irrigation Australia Conference 2008 (e.g. Brennan 2008; Hauber-Davidson 2008; Hennessy and Moller 2008; Moschis 2008), under the Urban Irrigation stream, provided evidence of the proliferation of such devices. These tools for micro-managing irrigation sites are promoted as part of outdoor demand management. Based on the fact that the water utilities in Australia have been focusing on trialling and promoting various micro-management tools, gadgets and calculators, a belief appears to prevail among technically-minded water managers that tools, gadgets and calculators can help with macro-management of urban irrigation demand. However, irrigation scheduling devices and efficient watering systems do not necessarily translate into water savings, unless they are supported by benchmarking and budgets that are indicative of the irrigation demand of the landscape. It must be realised that improving the efficiency of irrigation devices with micro-management tools is just one of the many ways of reducing irrigation demand and conserving water. Other useful ways of achieving
reductions in potable water use on landscapes include: using alternative sources of water such as grey water, rain water and treated effluent; designing low water-use landscapes (xeriscapes); promoting gardening practices that impact on water consumption by plants. Hence, in the absence of taking a macro-management approach to urban irrigation demand, the focus tends to be limited to micro-management tools and gadgets for improvement of irrigation efficiency and other demand management options tend to be overlooked. This thesis, therefore, takes the view that taking macro-management approach to urban irrigation demand can lead to development of policies and programs that facilitate sustainable ways of irrigating urban landscapes through a combination of various micro-management options.

1.2 Urban irrigation (outdoor) demand management: A review

1.2.1 Place of outdoor demand within urban water demand

Water demand by urban irrigation is recognised as outdoor demand by the water utilities that have the responsibility of supplying and managing the water used for irrigating urban green spaces. Other outdoor demands include the water used for washing cars and paved surfaces, and for topping up swimming pools to make up the water lost by evaporation. At the domestic level, irrigation constitutes 85–90% of the total outdoor water demand of households in cool and wet climates, and 75–80% of the demand in hot and dry areas (Vickers 2001). In the cool climates the remainder of the outdoor water demand is for car washing and hosing driveways and paved areas. In hot areas, in addition to these uses, outdoor water demand is used for evaporative air-coolers and swimming pools (Turner et al. 2004). In other words, regardless of climate, domestic outdoor water demand is predominantly used for the irrigation of gardens.

A significant component of overall domestic urban irrigation demand is the water applied to gardens and lawns of single detached dwellings. On a per household basis, the water demand of multiple residential units is typically much lower than that of separate houses. The reason for this disparity is the presence of gardens surrounding the detached dwellings that are of much greater size than the gardens associated with multi-residential properties (Vickers 2001; Loh and Coghlan 2003).
The indoor versus outdoor breakdown of average daily water demand for 13 North American cities is presented in Table 1-1. These data demonstrate the wide variation in outdoor water use across these cities. Hot, dry areas such as Texas, California and the south-western states typically have the highest per capita outdoor water use. The high volume of outdoor water use in these areas often greatly exceeds natural rainfall levels. In contrast, in regions such as New England and the Pacific Northwest that receive relatively higher rainfall and have cooler climates, 10–30% of the total water use is attributed to outdoor use (Vickers 2001). Hence, the average outdoor demand varies greatly across urban regions according to climate characteristics.

Table 1-1: Average water use in single detached dwellings of North America

<table>
<thead>
<tr>
<th>City</th>
<th>Litres per capita per day</th>
<th>% Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outdoor water use</td>
<td>Indoor water use</td>
</tr>
<tr>
<td>Waterloo, Ontario</td>
<td>38</td>
<td>227</td>
</tr>
<tr>
<td>Cambridge, Ontario</td>
<td>19</td>
<td>246</td>
</tr>
<tr>
<td>Seattle, Washington</td>
<td>76</td>
<td>190</td>
</tr>
<tr>
<td>Tampa, Florida</td>
<td>152</td>
<td>227</td>
</tr>
<tr>
<td>Lompoc, California</td>
<td>171</td>
<td>227</td>
</tr>
<tr>
<td>Eugene, Oregon</td>
<td>190</td>
<td>303</td>
</tr>
<tr>
<td>Boulder, Colorado</td>
<td>303</td>
<td>246</td>
</tr>
<tr>
<td>San Diego, California</td>
<td>379</td>
<td>208</td>
</tr>
<tr>
<td>Denver, Colorado</td>
<td>398</td>
<td>246</td>
</tr>
<tr>
<td>Tempe, Arizona</td>
<td>455</td>
<td>303</td>
</tr>
<tr>
<td>Phoenix, Arizona</td>
<td>569</td>
<td>284</td>
</tr>
<tr>
<td>Las Virgenes, California</td>
<td>682</td>
<td>265</td>
</tr>
<tr>
<td>Scottsdale, Arizona</td>
<td>682</td>
<td>303</td>
</tr>
</tbody>
</table>

Source: Adapted from Vickers 2001

Table 1-2 shows the average outdoor water use in the single detached dwellings of the major cities of Australian expressed as a percentage of total water use. Average outdoor water use in single detached family dwelling varies from 20% in Sydney (SWC 2007) to 35% in Melbourne (Roberts 2005) and 49% in Adelaide. In contrast, in Alice Springs, located in the hot, dry climatic zone of the Northern Territory, outdoor water use accounts for 65% of total water use, with 55% attributed to garden use and the remaining 10% to evaporative coolers (Turner et al. 2004).
Table 1-2: Outdoor water use in single detached dwellings of Australian cities

<table>
<thead>
<tr>
<th>City</th>
<th>Water use in single dwellings (litres per capita per day)</th>
<th>Outdoor water use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% of total household water use</td>
</tr>
<tr>
<td>Sydney (SWC 2007)</td>
<td>275</td>
<td>27%</td>
</tr>
<tr>
<td>Melbourne (Roberts 2005)</td>
<td>235</td>
<td>23%</td>
</tr>
<tr>
<td>Adelaide (Barton &amp; Argue 2005)</td>
<td>315</td>
<td>49%</td>
</tr>
<tr>
<td>Perth (Loh &amp; Coghlan 2003)</td>
<td>376</td>
<td>56%</td>
</tr>
<tr>
<td>Alice Springs (Turner et al. 2004)</td>
<td>647</td>
<td>65%</td>
</tr>
<tr>
<td>Canberra (Turner &amp; White 2003)</td>
<td>201</td>
<td>55%</td>
</tr>
</tbody>
</table>

1.2.2 Why manage outdoor demand?
Water demand management can be defined in many ways (Baumann 1998, White et al. 1998). In the context of urban irrigation demand management, water demand management can be defined as any measure that is intended to:

- Improve the efficiency of water use (e.g. using efficient watering systems)
- Adjust the nature or process of the water-using service to use less water or lower quality water (e.g. shifting to low water-using plants, making use of greywater to irrigate the garden).
- Shift timing of the water use to achieve efficiency gains (e.g. switching the time of watering to reduce evaporative losses) (Brooks et al. 2007).

Often demand management can be considered to be limited to water-efficient technology and equipment. In essence, however, demand management is a governance concept (Brooks et al. 2007). At the operational level, it is about
influencing the water demand of the population through policies and programs that moderate and manage demand in a way that the same service benefit is derived from less water. Water-efficient technology is just one of many ways of reducing the use of potable water. Other means might include redesigning the service to reduce water use, or providing the quality of water appropriate to the service—in other words, switching to lower quality sources of water for non-potable requirements.

Table 1-3 lists the various demand management goals that are achieved by targeting different kinds of demands. Outdoor demand provides the most scope for demand management as it is able to meet more than one management goal. This is primarily because:

- Outdoor (urban irrigation) demand is a significant proportion of total urban water demand.
- Moderating or reducing outdoor demand does not affect personal convenience or hygiene, as in the case of indoor water demand. Therefore, it offers the scope to change the time and/or frequency of use, and even to restrict use during emergencies such as drought.
- Outdoor demand is dependent upon rainfall and rate of evaporation and therefore is highly seasonal.

<table>
<thead>
<tr>
<th>Management goal</th>
<th>Targeted demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoid capital costs of meeting peak demand</td>
<td>Peak demand (outdoor)</td>
</tr>
<tr>
<td>Avoid costs of increased sewage system capacity</td>
<td>Indoor demand</td>
</tr>
<tr>
<td>Reduce withdrawal from water supply source</td>
<td>Total demand (indoor + outdoor)</td>
</tr>
<tr>
<td>Reduce net consumption (re-use effluent) (e.g. drought)</td>
<td>Outdoor demand</td>
</tr>
<tr>
<td>Cope with short-term supply problem (e.g. drought)</td>
<td>Seasonal demand (outdoor)</td>
</tr>
</tbody>
</table>

Adapted from Woodard (2004)

There are two distinct approaches to managing outdoor water demand: regulatory and non-regulatory. Regulatory approaches include pricing and water restrictions. The non-regulatory approach refers to the market-based conservation policies and programs implemented by water utilities to facilitate the adoption of water-saving measures by water users.
1.2.3 Regulatory approaches to outdoor demand management

Conventional approaches to managing outdoor demand to achieve one or more of the management objectives listed in Table 1-3 include pricing and mandatory water restrictions. Pricing is a conventional way of managing water demand. This is because among the various types of water demand within a household, urban irrigation demand is the most elastic relative to total household demand (Baumann 1998). Price elasticity of demand is defined as percentage change in demand caused by 1% change in price (Woodard 2004). This is why water utilities manage total water demand by relying on the reduction in outdoor demand that is likely to occur as a result of price increases.

The rate and structure of pricing is based on the objectives of the pricing policy, which can be one or any of the following (Woodard 2004):

- subsidise all water users or subsidise the municipal general budget
- subsidise certain water uses, e.g. parks, desirable industry, pools
- subsidise growth or make growth pay its own way
- provide stable, predictable revenue to utility
- avoid customer/voter backlash
- have rates reflect cost of service
- reward water conservation and punish ‘water waste’.

A pricing policy aimed at reducing outdoor demand generally takes the form of uniform marginal price, an increased block tariff or two-tier pricing (Olmstead et al. 2003). Under uniform marginal pricing, water is priced at a uniform rate for any volume of water consumed. In the case of an increasing block tariff, a volume of water equivalent to base demand (generally equal to anticipated indoor demand) is charged at a lower rate, known as the base charge or first tier price. Any amount of water consumed over and above base demand is charged at a rate higher than base charge, making it the second tier of the two-tier price structure. Olmstead et al. (2003) found that elasticity is higher, and demand is lower, among households facing block prices than those households facing uniform marginal prices. The impact of the price structure on demand was found to be greater than the impact of marginal price itself.
Woodard (2004) noted that a pricing policy that is set with the objective of rewarding water conservation and punishing ‘water waste’ is generally based on the following assumptions about the consumers:

- they are fully aware of price structure
- they are fully aware of amount of water [they use] for various purposes
- they are rational
- water bills are a significant portion of overall budget.

Studies show that using prices to manage water demand is more cost effective than implementing non-price conservation programs (Olmstead and Stavins 2008). Pricing also has advantages in terms of monitoring and enforcement. However, pricing as a policy to manage outdoor water demand has its limitations. For example, pricing alone is not capable of influencing domestic water demand to the level that is required to maintain water storages at sustainable levels (Grafton and Kompas, 2007) unless it is efficiently set to recover the cost of supplying water in the present and future along with opportunity costs that reflect the impact on the environment. As in any policy context, political considerations tend to favour non-price policies over pricing for water conservation and demand management. This is one of the reasons why most water utilities around the world have traditionally set a heavily subsidised price that is much lower than the long-term marginal price. More recently, however, owing to extended periods of drought, there is a trend among water utilities in Australia and North America to switch to prices that reflect the true and full cost of water service. Increasing numbers of water utilities are combining incentive-oriented conservation programs with price increases or changes to price structure with the view to reducing consumer resentment and political backlash (Woodard 2004).

While pricing may curtail outdoor demand on a long-term basis, enforcing water restrictions is a regulatory approach adopted by water utilities to achieve short-term reductions of outdoor demand in times of drought-induced water shortages. Urban water utilities enforce water restrictions of varying severity based on quantitative measures of water storage levels used as the trigger for restrictions (Brennan et al. 2007). Restrictions generally involve prescribing the time and frequency of using sprinklers or other garden watering methods, including hand-held hoses. The utilities enforce water restrictions as a law, generally for a fixed period of time. Restrictions are generally removed when water storage levels have increased to ‘secure levels’ following rainfall. Anyone found breaching a mandatory restriction is liable to a penalty in the form of a heavy fine.
Several studies have evaluated the effectiveness of water restrictions and pricing as a way of managing domestic water demand. Anderson et al. (1980) found that during the six week-long water restrictions on lawn watering that were imposed in Fort Collins (Colorado) to cope with the drought that commenced in 1977, water use decreased 41% below the previous year’s use. Kenney et al. (2004) compared water savings achieved from various types of water restrictions enforced by eight water utilities in Colorado to cope with the water shortage during the 2002 drought. They found that mandatory restrictions were an effective tool for coping with drought. Under mandatory restrictions, savings measured in expected use per capita ranged from 18% to 56%. In contrast, voluntary restrictions resulted in savings of only 4% to 12%. The study found that water utilities with the most stringent restrictions achieved the greatest savings.

In recent times, with extended periods of low rainfall becoming a norm and high climate variability experienced by almost every Australian state, water users have been on different levels of water restrictions for prolonged periods that extend well over one year (Brennan 2007). Hensher et al. (2006) studied Canberra households’ and businesses’ willingness to pay to avoid drought water restrictions, using stated choice experiments. The study found that water users appeared willing to tolerate high-level restrictions for limited periods each year, compared with paying higher water bills.

However, the substantial water savings that may be achieved by water restrictions come at the cost of the urban green space and the social, environmental and economic values associated with it (Fam et al. 2008). In many Australian cities the quality of urban green space has been adversely affected as a result of the past few years of extended water restrictions. In a bid to save their gardens from further deteriorating, it is reported that the community is willing and ready to play an active role in conserving water at the household level (Brownlee and Stephens 2004). This is reflected in the increasing numbers of people who have implemented water-saving measures, particularly with respect to outdoor water use on their lawns and gardens. These range from installing rainwater tanks, using kitchen and laundry wash-water to irrigate their gardens, and making a switch to low water-use plants. It is in this context that developing policies and programs that involve the participation of the residents becomes important to achieving the maximum demand management potential in outdoor water use.
1.2.4 Non regulatory approaches to managing urban irrigation demand

A non-regulatory approach to managing outdoor demand relies on market-based programs and policies (Baumann 1998). While outdoor demand management programs may appear to take different forms, a careful review of these programs shows that they essentially target the following factors, which have a direct influence on the outdoor demand of a domestic garden:

- landscape design
- watering system and methods
- soil management
- selection of landscape planting
- use of alternative sources of water.

The market-based approach aims to employ market or policy instruments to promote and facilitate reduction in water demand. This approach relies on consumers making the switch to water-saving products, services, practices and behaviour. The policy instruments used to promote the outdoor demand management programs may be categorised into three types:

a) *Communication and education* This policy instrument is most common. It aims at creating awareness among home owners about lawn designs, watering and gardening practices that will result in a home garden that uses less water.

b) *Economic incentives* in the form of subsidies and rebates to facilitate the uptake of products and services that will improve water-use efficiency in the garden or reduce the demand for potable quality water for garden use.

c) *Best practice and benchmarking* are employed by water utilities to set performance standards and to provide guidelines for best practice with respect to landscape design, gardening practices and watering systems and practices.

Table 1-4 provides examples of urban irrigation demand management programs that are designed using each of the policy instruments and aimed at targeting different factors that determine urban irrigation demand.
Table 1-4: An overview of non-regulatory outdoor demand management programs

<table>
<thead>
<tr>
<th>Market-based policy instrument</th>
<th>Targeted demand factor</th>
<th>Education</th>
<th>Economic incentives</th>
<th>Best management practice and benchmarking</th>
</tr>
</thead>
</table>
| Landscape design               |                        | • Promotional information on:  
• designing water-wise garden  
• importance of creating garden zones by grouping together plants with similar water requirements (Hydro-zoning)  
• providing suitable microclimate to plants | • Subsidised landscape advisory service | • Demonstration garden  
• Code of practice for landscape design |
| Watering methods and system    |                        | • Information on duration and frequency of watering  
• Prescribing the amount of water the garden requires (E.g. program called Tap Tag of Sydney Water Corporation which tagging the garden tap with the watering prescription following an assessment of the garden) | Rebates on water efficient technology:  
• weather-based irrigation controls  
• soil-moisture sensors  
• rain gauge and sensor  
• drip systems  
• micro-irrigation system | • Code of best practice for irrigation systems  
• Labelling scheme to help consumers choose efficient equipment  
• Landscape water budgets and benchmarks |
| Soil management                |                        | Information on benefits of:  
• mulching  
• composting  
• soil conditioners and modifiers to improve water retention | • Promoting the use of soil conditioners, e.g. water crystals, mulches | • Guidelines and case studies on best (soil) management practices |
| Landscape plantings           |                        | • Web-based database to help the selection of low water use plants and turf  
• Promoting concepts of xeriscapes and rock gardens | | |
| Use of alternative water sources |                      | | • Rebate on installation of rainwater tanks and grey water reuse system | |

1 Based on a review of outdoor demand management programs promoted on the websites of urban water utilities across Australia (e.g. Sydney Water Corporation, South East Water, City West Water, Water Corporation of Australia) and North America (e.g. California Urban Water Conservation Council, Denver Water, Aurora Water, Seattle Water, City of Phoenix, City of Austin).
1.2.5 Approach to urban water demand analysis

Analysis and forecasting of urban water demand is undertaken by water utilities when planning for water resources to cater for the growth in water demand associated with future population growth (Baumann et al. 1998; White et al. 1998). Traditionally, demand forecasting was based on historic trends of per capita water demand (Baumann 1998). Sometimes water resource managers would develop strategies to meet future demand based on multiple regression techniques using a range of variables such as population, income, price of water and periods of restriction. Both strategies traditionally included developing new supply sources to meet the identified demand (Baumann et al. 1998). Now, however, as planners increasingly recognise the value of water conservation, demand-management strategies are emerging as more cost effective than the development of new supply sources (the latter is also referred to as supply-side strategy or solution) (White et al. 1998). A demand-management strategy involves making investments in improving water-use efficiency to reduce demand. This is in contrast to supply-side strategy, which aims to increase the water supply to match the overall increase in demand (Baumann et al. 1998).

To enable development of effective demand-management strategies, it was also necessary to develop a demand forecasting technique more sophisticated than extrapolation of historic trends, or undertaking multiple regression analysis based on external variables (Baumann et al. 1998). It was also desirable that demand forecasting adopt a ‘service approach’, unlike the traditional methods that viewed water as a ‘commodity’ that needed to be supplied to meet increasing demand (White et al. 1998). In recent years, end-use analysis (EUA) has evolved as the demand forecasting methodology most appropriate for the development of demand-management strategies (White and Fane 2002). EUA involves disaggregating the water demand to the maximum extent possible, including sector breakdown (residential—single family; residential—multi-family, industrial, commercial and institutional), broad categories within a sector (such as indoor, outdoor use) and specific end-use data (toilet flushing, showerheads) (White et al. 2004).

Sydney Water Corporation (SWC) was one of the first water utilities in Australia to apply EUA for development of a comprehensive demand-management program based on end-use analysis (Mitchell et al. 2004). SWC has invested approximately $100 million since 1999 in such programs. Most resources have been invested in programs that aim to reduce the per
capita water demand in residential indoor use (SWC 2007). Outside Australia, several water utilities in North America have developed and advanced the application of end-use analysis over the past two decades; a detailed review of this is presented in section 1.2.6 when discussing water use studies.

Most end-use studies have undertaken an in-depth analysis of residential indoor water use (Roberts 2005; Mayer et al. 1999). Outdoor water use is not analysed to the same level of detail as indoor water use in these studies. This is due to lack of data in relation to technical features of prevalent outdoor water-using equipment, data pertaining to their ownership in the population and stock in the market for future sales, garden and landscape characteristics, and user behaviour with respect to gardening practices and watering methods (White et al. 2004).

Lack of appropriate data has greatly hindered progress in both capturing and measuring efficiency improvements in the residential landscape sector. While it is recognised that the potential for saving water is substantial (Vickers et al. 2001; Gleick et al. 2003), the tools to quantify and evaluate specific savings on urban landscapes have not yet been developed. Thus most agencies have limited data on the characteristics of their residential landscape and public open space that contribute to the urban irrigation demand. They often do not have reliable estimates of outdoor water use, at either residential or landscape scale, the type of plantings present or irrigation methods used. The problem is exacerbated because landscaped properties typically do not have dedicated irrigation meters. Site-specific information is therefore difficult to obtain. Because of the expense involved in overcoming these impediments, outdoor water-use data collection and analysis is not commonly undertaken by urban water utilities. Nevertheless, there have been attempts to study outdoor demand.
1.2.6 Review of outdoor water use studies

Studies on outdoor demand analysis can be categorised into two kinds:

1. Those aimed at obtaining a breakdown of total household demand into indoor demand and outdoor demand, at the individual household level.
2. Those aimed at predicting outdoor demand based on factors that directly or indirectly influence outdoor demand.

Under the first category, the Metropolitan Water Authority of Western Australia conducted one of the most comprehensive studies of domestic water undertaken in Australia (Loh and Coghlan 2003). The study was conducted in metropolitan Perth on two occasions encompassing a 20-year interval (1981–82, 1998–2000). The aim was to determine how water was used by the domestic sector and to identify the various household characteristics and other factors influencing the level of water use. It was observed that indoor water demand was relatively constant throughout the year while outdoor water use varied with season, with a summer peak. The study also found that indoor water use was essentially influenced by household size, whereas outdoor water use was strongly linked to other characteristics such as the size of the house block, irrigated (garden) area, tenure and rateable value.

A study of domestic water use commissioned by the American Water Works Association Research Foundation (AWWARF) pioneered the application of the ‘end-use analysis’ approach to disaggregate total household water use into the components contributed by each end-use (Mayer and DeOreo 1999). The report on the study, titled Residential End Use Water Study (REUWS), represented a time and place snapshot of water use in single-family homes in 12 North American locations. The aims of the study were: a) to determine per capita water usage for each identified end-use; b) to predict water savings available from indoor conservation measures; and c) to develop predictive models for indoor demand. Data were collected from each of the 12 study sites using: a) historic metered consumption data from billing records from a random sample of 1,000 single-family detached residential accounts; b) household information obtained through a mail survey sent to each of the selected 1,000 households; c) approximately four weeks of specific data on the end-uses of water collected from a total of 1,188 households; and d) supplemental information, including climate data and information specific to each participating utility. In addition, water consumption for
various end-uses was measured using compact data loggers and flow trace analysis software. (A flow trace is a record of flow through a residential water meter, recorded at 10-second intervals, that provides sufficient resolution to identify the patterns of specific fixtures within the household.) The annual water use breakdown between indoor and outdoor demand across all study sites was reported as 42% indoor and 58% outdoor. The study also reported that the mix of indoor and outdoor uses was strongly influenced by annual weather patterns.

In Australia, a study of domestic water use was undertaken using the same approach as the AWWARF study. Known as the *Yarra Valley Water End Use Study of Melbourne Metropolitan*, it was commissioned by the Water Resources Strategy Committee for the Greater Melbourne Area in 2001 (Roberts 2005). It provided a detailed disaggregation of indoor demand. The outdoor demand was estimated as the difference in usage between the total household demand and the indoor demand. Indoor water use showed no seasonal variation while once again outdoor water use did show variation with season. In addition, outdoor water use varied widely across the metropolitan area.

In the absence of detailed water use studies, a breakdown between indoor and outdoor domestic water use was estimated for Adelaide using bi-annual water meter data, and monthly data of the metropolitan water treatment plant discharges (Barton and Argue 2005). The bi-annual water meter readings were used to separate the total water consumption into ‘domestic’ and ‘other’ use categories, and monthly data from the metropolitan water treatment plant discharges were used to obtain partitioning of indoor and outdoor water demand and in establishing the monthly trends of outdoor water demand. In Brisbane city, Stewart et al. (2006) estimated the indoor–outdoor partitioning of total household water use by employing three different independent indirect methods that involved: a) using water reservoir flow analysis; b) sewer flow data; and c) household survey. The study was able to confirm and corroborate using the three independent methods that 21% of total household water use in Brisbane is used outdoor.

A comprehensive water use study commissioned to determine the water-saving potential of various urban water end-uses across Californian cities was reported on by Gleick et al. (2003). The water-saving potential of indoor end-uses of water was based on assumptions derived from previous end-use studies on indoor water. In the absence of any end-use study that had direct measured outdoor water use, Gleick et al. employed various indirect methods
of estimating domestic outdoor water use across different Californian regions. The four indirect methods, which made use of available data on population and metered consumption data for the domestic sector and assumptions relating to outdoor water use, were: a) the Hydrologic method, which made assumptions about the percentage of domestic water use that was outdoor; b) the Summer-Winter method, which assumed that outdoor demand was equal to the difference between demand in summer and winter months; c) the Minimum Month method, which assumed that the lowest use month represented indoor water use which did not vary with the season (and month), and hence outdoor water use was estimated as the difference between the total water use for the month and the water use in the lowest (water use) month; and d) the Average Month method, which made use of the average of the three lowest water use months, rather than the Minimum Month method to represent indoor water use.

Estimating outdoor water use, whether by household survey, direct measurement or indirect methods, is important for quantifying current irrigation demand. However, the information gathered by the studies cited above does not provide any indication of the potential that exists for managing the demand. To obtain an estimate of the water-saving potential that exists for managing urban irrigation demand, it is necessary to compare what residents are actually applying to their gardens with the irrigation water required to meet the biophysical need of the gardens that they are maintaining.

In addition to determining how much water is used, some outdoor water use studies have aimed at correlating outdoor water use with various influencing factors and modelling domestic outdoor demand. Coombes et al. (2000) developed an outdoor demand model that would predict the daily outdoor water use of a household based on the probability that the home owner would apply water to the garden. The model took account of factors that are typically considered by the householder in making a decision to water outdoors. These variables included the number of dry days preceding a wet event, amounts of precipitation and maximum daily temperatures.

In a study by Syme et al. (2004), estimates made of outdoor water use for 397 households in detached housing in Perth, Western Australia, were correlated to a variety of socio-demographic variables measured for the participant households. These variables included income, block size, swimming pool ownership and so on. Five latent attitudinal or quality of
life variables were also measured. These included qualitative factors such as: the importance of a garden and natural space for personal lifestyle satisfaction; interest in gardening; attitudes towards the garden as a source of recreation; attitudes to water conservation; and a social desirability scale. Outdoor water use was then modelled using structural equations involving the latent variables. As expected, socio-demographic variables such as block size or swimming pool ownership were found to influence total water use. Lifestyle, garden interest and garden recreation activities were found to be related, and together had a direct influence on outdoor water use. Attitudes towards water conservation also directly affected outdoor water use.

In another study by Troy et al. (2005), the metered consumption data of Sydney residents for the period 1987-2003 was correlated to built form (detached dwelling vs. multi-residential units), socio-economic (income, occupancy, ownership vs. rented, etc.) and weather factors. Aggregate data at census district level from 140 census districts were used to study the correlations. With respect to outdoor water use, it was found, contrary to expectation, that there was no relationship between summer water consumption of houses in the selected CDs and the size of the allotment (as a surrogate for garden area). Neither was a relationship found between summer water consumption and rainfall over the three summer months in 2001. Based on these results, Troy concluded that Sydney households generally maintain a similar level of outdoor water consumption throughout the year regardless of rainfall or soil moisture conditions. The study also found little difference between summer and winter consumption. This observation, coupled with the fact that summer rainfall in Sydney is typically higher than winter rainfall, led to the conclusion that Sydney homes tend to rely on rainfall to irrigate their gardens except when there may be extended dry spells.

An outdoor demand model which describes the relationship between irrigation (water use) and lawn quality was central to a study aimed at estimating the welfare cost of water restrictions (Brennan 2007). Using the outdoor demand model, the study analysed the impact of sprinkler restrictions on consumer welfare and their efficacy as a demand management tool. Brennan found that for a typical consumer, complete sprinkler bans achieve marginally greater water savings compared to milder water restrictions, but at a significant welfare cost to the household.
While these modelling studies provide information on outdoor water use relative to different social and demographic characteristics and climatic factors, they are unable to quantify the water savings that can potentially be achieved or to what extent and how outdoor water use may be influenced and therefore managed.

To summarise, this review of the state of urban irrigation demand management highlights two things:

i) Both direct and indirect methods are available to estimate outdoor water use of existing landscaped properties. However, currently there is no systematic way of determining the demand management potential of existing outdoor demand. Demand management potential for existing landscapes is the difference between actual outdoor water use being applied on the existing landscapes and the amount of external water application required in the form of irrigation to meet the biophysical need of the existing landscapes.

ii) While there are studies that have correlated indirect factors to outdoor demand, there is a need to develop an understanding of how the biophysical factors that have a direct influence on urban landscape water requirements interact with one another to contribute to the total outdoor demand. These biophysical factors include micro- and macro-climate, soil, plant type and planting composition, and landscape area. Such an understanding could lead to the development of a biophysical model to estimate the irrigation water requirement of an urban landscape.

1.3 Methods of estimating irrigation water requirement of urban landscapes: A review

While the science of the irrigation of agricultural crops is well established, the science of urban landscape irrigation is less well developed. There are differences between the irrigation of agricultural crops and irrigating urban landscapes, the fundamental difference being that for agricultural crops a quantifiable output (crop yield) corresponding to the irrigation input is measurable. In contrast, the output of irrigation on an urban landscape element such as a domestic garden, golf course or soccer field is not readily quantifiable.

Another difference is that agricultural crop fields tend to be more homogeneous with respect to plant composition when compared to urban landscapes such as domestic gardens, parks
and ornamental landscapes in public open spaces. The lack of homogeneity also influences the micro-climate affecting the plants which, in turn, has a direct influence on the estimation of irrigation water requirements (Jones 1992). This is why the water–atmosphere–soil–plant interactions developed for irrigated agriculture are not directly applicable to urban landscapes, and make the estimation of irrigation water requirement of urban landscapes a challenge (Connellan 2004).

The optimum amount of irrigation water required by plants is determined as the relationship between the amount of water the plants lose by evapo-transpiration (ET) and local soil moisture characteristics Kirkham (2005).

Evapo-transpiration rates have been established for turf grass and various agricultural crops (Kim & Beard 1988; Liu et al. 2002; Kang et al. 2004). The conventional method of measuring evapo-transpiration rates for agriculture crops makes use of the known crop coefficient (Kc) for the particular crop. Crop coefficient is unique to each crop or plant type. It is the ratio of the evapo-transpiration rate of irrigated cool-season reference grasses (ET₀) to the evapo-transpiration rate of irrigated test plants (ETc), both of which have been measured in well-controlled field plots (Kirkham 2005). Historical average values of ET₀ are available for various locations from local weather stations. These values are generally used along with Kc to determine ETc for a given crop or plant. However, ETc values for urban landscapes are more difficult to establish by these conventional methods used in agriculture for the following three main reasons (Costello et al. 2000):

- Unlike an agriculture crop or turf grass, a landscape is composed of many species and a mixture of vegetation types (e.g. trees, shrubs, groundcovers).
- Landscapes vary considerably in density of plantings. A newly planted landscape, for example, has much less evaporative leaf surface area than a mature planting.
- Many urban landscapes include a range of microclimates such as cool, shaded, protected areas and hot, sunny, windy areas. These variations significantly influence ET.

1.3.1 Estimation of crop water requirement in irrigated agriculture
Irrigation science was developed for irrigated agriculture, where water supply is critical to the quality and quantity of crop yield. ‘Crop water requirements’ (cf. FAO 1979, 1998;
Carruthers and Clark 1983; Michael 1978) are defined as the water crops need to reach their maximum (or near-maximum) yields at a certain location and season. Such concepts and related calculation methods are widely used by irrigation engineers and, because of their endorsement by academics and professionals, have become the standard to calculate the daily water requirement of a crop (Lascano 2000).

The crop water requirement is estimated on the basis that water needed to be applied externally in order to replenish all or part of the evapo-transpiration by which water is lost to the atmosphere from the soil and the plants. Accordingly, the total amount of water lost by evapo-transpiration during a specific period gives an estimate of the amount needed to be replaced by irrigation. The calculation method that is currently widely used to estimate the crop water requirements is based on an empirical factor called the crop coefficient (Kc) applied to a hypothetical concept of potential or reference evapo-transpiration (ET₀) (Costello et al. 2000).

\[ \text{ET₀} = \text{the amount of water that evaporates from a hypothetical uniform growth of 10 mm to 20 mm tall cool-season grass in an open-field condition that does not suffer a water deficit} \]

\[ \text{The crop coefficient (Kc) is empirically determined from field studies. Water loss from the crop (ETc) is measured over an extended time period, while reference evapo-transpiration (ET₀) is estimated at the location where the crop is grown, and Kc is calculated as follows:} \]

\[ \text{Kc} = \frac{\text{ETc}}{\text{ET₀}} \text{ (Allen et al. 1998)} \]

The crop coefficient (Kc) is the fraction of water lost from the crop relative to the reference evapo-transpiration. For annual crops, Kc increases through the growing season as leaf area increases. This reflects the observation that evaporation from dry, bare soil is low (reference). Typically, crop water loss is less than reference evapo-transpiration and, therefore, the crop coefficient is less than 1.0, except under strongly advective conditions (e.g. in a desert region) (Allen et al. 1998).

Based on long-term field studies, crop coefficients for agricultural crops and turf grasses are well established (Allen et al. 1998). Values for a selection of perennial tree crops or vines are
given in Table 1-5. These values give an indication of the range of values the crop coefficient takes depending on the water requirement of the crop during low growth and high growth season. Consequently, a farmer can make use of the crop coefficient corresponding to specific crops to estimate the water requirement using the following formula:

\[
\text{Crop water requirement} = \text{Crop Evapo-transpiration (ETc)} = \text{Crop Coefficient (Kc) x Reference Evapo-transpiration (ET}_0) \\
i.e. \text{ETc} = \text{Kc} \times \text{ET}_0
\]

A farmer will generally aim to replenish the amount of water lost by evapo-transpiration in order to maximise economic yield (Allen et al. 1998). Different values of Kc for different growth phases are used to ensure that irrigation replenishes an amount equal to ETc, less any rainfall (Allen et al. 1998).

Table 1-5: Example of tree crop coefficient values (Source: Costello et al. 2000)

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Kc values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low (during low growth in early and late season)</td>
</tr>
<tr>
<td>Deciduous orchard</td>
<td>0.50</td>
</tr>
<tr>
<td>Deciduous orchard with cover crop</td>
<td>0.98</td>
</tr>
<tr>
<td>Grape</td>
<td>0.06</td>
</tr>
<tr>
<td>Olive</td>
<td>0.58</td>
</tr>
<tr>
<td>Pistachio</td>
<td>0.04</td>
</tr>
<tr>
<td>Citrus</td>
<td></td>
</tr>
<tr>
<td>Turfgrass (cool season species)</td>
<td>0.80 year-round</td>
</tr>
<tr>
<td>Turfgrass (warm season species)</td>
<td>0.60 year-round</td>
</tr>
</tbody>
</table>

Crop coefficients Kc take account of:
- the water use characteristic, the species factor
- uniform plant density associated with mono cropping
- exposure to full sun that is characteristic of open fields
- crop growth requirements when not limited by water supply (Allen et al. 1998).

\[\text{It may also reflect the level of water stress the species can cope with; e.g. the lower coefficient of warm-season turf grass is reflective of the fact that it can cope with water stress relatively better than cool season species, thus requiring less water for its survival and growth.}\]
However, these conditions are not usually present in urban settings. This is because landscape plantings are characterised by:

- the presence of isolated plant specimens, or mixed plantings with varied water requirements and different conditions of hardening;
- varying plant densities that result from heterogeneous plantings;
- the influence of microclimate that is created by adjacent structures and surfaces;
- the outcome that is assessed based on amenity and aesthetic value, which is not amenable to objective valuation and is unlike biomass production or other estimates of yield, based on which the outcome of irrigation of agricultural crops is assessed (Costello et al. 2000).

These characteristics of landscape plantings prevent the application of the crop coefficient method for predicting or determining landscape water use.

1.3.2 Landscape coefficient method ($K_L$ method)
A research group based in University of California, USA, developed the landscape coefficient method to address the need for an approach that is more suited to landscape plant species (Costello et al. 2000). To facilitate the use of this method, the group compiled a list of landscape plant species commonly planted in Californian urban areas and classified each species by its water use characteristics. The classification is based on field study, involving qualitative observations, undertaken by a committee of experienced landscapers and horticulturists. Although not scientifically based, this classification of landscape plant species is useful to underpin an estimate of the water requirement of an urban landscape, particularly in the absence of research-based information. The Californian research group’s study culminated in a publication that has become one of the benchmark references on the subject, *A Guide to Estimating Irrigation Water Needs of Landscape Plantings in California: The Landscape Coefficient Method and WUCOLS III* (Costello and Jones 2000). WUCOLS is an acronym for ‘water use classifications of landscape species’.

The landscape coefficient method developed by Costello et al. (2000) adapted the crop coefficient method to develop the landscape evapo-transpiration formula, whereby the water loss in a landscape by evapo-transpiration over a given period of time, $ET_L \text{ (time)}$, is expressed
as the product of a landscape coefficient \( K_L \) and reference evapo-transpiration \( E_{TO} \) (time) over the same period of time (Costello et al. 2000).

\[
E_{T_L \text{time}} = K_L \times E_{TO \text{time}}
\]

The landscape coefficient, \( K_L \), serves the same purpose in estimating water requirement as the crop coefficient, \( K_c \). However, in addition to taking account of the species factor that characterises its water use, it takes account of the two unique characteristics, plant density and microclimate, that differentiate landscape plantings from irrigated agriculture.

\( K_L \) as a product of three factors:

\[
K_L = k_d \times k_{mc} \times k_s
\]

where

- \( k_s = \text{species factor} \) to account for water use characteristics of the plant species, the value of which varies from 0.2–1.2 (Table 1-6)
- \( k_d = \text{plant density factor}, \) the value of which varies from 0.2–1.3 (Table 1-7)
- \( k_{mc} = \text{microclimate factor}, \) the value of which varies from 0.5–1.4 (Table 1-8).

Because of the paucity of research on landscape species, the \( k \) factors used in the landscape coefficient method are based on qualitative data, such as previous experience of horticulturists and landscape managers, and are empirical in nature, are subjective and are based on species used in the USA (Costello and Jones 2000).
**Species factor ($k_s$)**

The species factor, $k_s$, is applicable to all plant types including trees, shrubs, groundcovers and turf. The values for the species factor given in Table 1-6 are based on water-use studies for landscape species and on data that may be applicable from agricultural crops (Costello et al. 2000). The Californian research group has compiled the species factor, based on field observations, for over 1,800 species that are used in urban landscapes. These values are presented in Part 2 of WUCOLS III (Costello and Jones, 2000). Species factor values can be found by looking up the species under consideration, and selecting an appropriate value from the category. The categorisations of ‘high’, ‘average’ and ‘low’ for the species factor are arbitrary and indicate the level of water requirement of a species relative to another. For example, amongst shrubs, *Camellia*, *Nandina* and *Agapanthus* represent high, average and low water using species respectively.

The high water using shrubs have been found to have lower species factor ($k_s$) value compared to the high water using trees and groundcover. This indicates that the bio-physiscal water requirement of high water using shrubs tends to be less sensitive to plant physiology than that of the high water using trees and groundcover.

### Table 1-6: Species factor $k_s$ for landscape components

<table>
<thead>
<tr>
<th>Landscape components</th>
<th>High water need</th>
<th>Average water need</th>
<th>Low water need</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td>0.9</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Shrubs</td>
<td>0.7</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Groundcover</td>
<td>0.9</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Mixture of trees, shrubs and groundcover</td>
<td>0.9</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Cool-season turf grass</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>Warm season turf grass</td>
<td>-</td>
<td>0.6</td>
<td>-</td>
</tr>
</tbody>
</table>

*Source: McCabe 2005*
**Plant density factor, $k_d$**

The plant density factor, $k_d$, is rated high, average or low depending on the extent of plant growth and amount and arrangement of foliage and leaves, and the extent to which the soil surface is exposed or covered by the plant growth (Costello et al. 2000). The assumption is that evaporation from bare soil is low and that most of the ETc is from plant transpiration. This assumption will not hold if soil surfaces are frequently wet (Hillel 1987). Accordingly, the plant density factor is considered:

- high, when plantings of mixed vegetation type are grouped together, as they tend to have greater collective leaf areas than plant groups of single type of vegetation;
- moderate or average, when fully grown plantings of single vegetation type are found;
- low, when the landscape is sparsely planted and has leaf area less than matured or densely planted landscapes.

**Table 1-7: Density factor $k_d$ for landscape components**

<table>
<thead>
<tr>
<th>Landscape components</th>
<th>High density</th>
<th>Average density</th>
<th>Low density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td>1.3</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Shrubs</td>
<td>1.1</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Groundcover</td>
<td>1.1</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Mixture of trees, shrubs and groundcover</td>
<td>1.3</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Turf grass</td>
<td>1.0</td>
<td>1.0</td>
<td>0.6</td>
</tr>
</tbody>
</table>

*Source*: McCabe 2005

*Note*: $K_d$ values shown in the table assume that bare soil surfaces within the landscape planting are not wetted by irrigation. Otherwise, $K_d$ should be increased 10% to 20% due to soil surface evaporation, especially for trees and shrubs (McCabe 2005).

**Microclimate factor, $k_{mc}$**

The microclimate factor, $k_{mc}$, is rated high, average or low depending on the extent of exposure the landscape plantings have to sun and/or any impervious surface that can radiate heat in its vicinity, thus causing advection (Jones 1992). Accordingly, it is considered:
- high, when 50% or more of the landscape plantings in a garden are exposed to full sun or afternoon sun for a good part of the day or are in the proximity of a hard surface that is exposed to full sun or afternoon sun for a good part of the day;
- average or moderate, when 50% or more of the landscape plantings in a garden are exposed to part sun/shade or morning sun for a good part of the day;
- low, when 50% or more of the landscape plantings in a garden are in full shade for a good part of the day.

The $k_{mc}$ values shown in the Table 1-8 indicate that the bio-physical water requirement of high water using species tends to be more sensitive to micro-climate than the average or low water using species,

**Table 1-8: Microclimate factor $k_{mc}$ for landscape components**

<table>
<thead>
<tr>
<th>Landscape components</th>
<th>High</th>
<th>Average</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td>1.4</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Shrubs</td>
<td>1.3</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Groundcover</td>
<td>1.2</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Mixture of trees, shrubs and groundcover</td>
<td>1.4</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Turf grass</td>
<td>1.2</td>
<td>1.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*Source: McCabe 2005*
Table 1-9: Worksheet for estimating landscape water requirement

Calculating landscape water requirement

Table 1-9 is an excerpt from the WUCOLS III Guidebook showing the steps used in calculating the water requirement by landscape plants. Here landscape water requirement is estimated on a monthly basis, and is expressed as follows:

\[ LWR_{\text{(month)}} = ET_{L_{\text{(month)}}} \]

where
ET_L(month) = K_L * ET_O (month)

where

K_L = landscape coefficient that varies from 1.6 to 0.5, depending on the combination of planting density, microclimate and water using characteristics of plant species

ET_O (month) = reference evapo-transpiration for the month

The major limitation to the landscape coefficient method, which makes it unsuitable to use for estimating landscape irrigation budget for demand management purposes, is that it does not account for rainfall. This may be acceptable in the Mediterranean-type climate of California with hot dry summers where irrigation is required, but it will not be adequate in Australian cities like Sydney and Melbourne, where rainfall can occur in any month.

1.3.3 Modified landscape coefficient method that accounts for rainfall (K_L + P_eff method)

This is a variation of the landscape coefficient method that takes account of the rainfall during the month or quarter (McCabe et al. 2005), incorporating the concept of ‘effective rainfall’. Effective rainfall is defined as the proportion of the recorded rain that is actually usable by the plants. As shown in Table 1-10, the effectiveness factor varies between 0.45 and 0.68 depending upon on the amount, intensity and duration of each rain event in the month, soil type and its available water-holding capacity, intake rate, plant type and root depth, and amount of moisture in the root zone prior to the rain event (McCabe 2005). Taking account of effective rainfall, the mathematical expression used to estimate landscape irrigation water requirement using this method is as follows:

LWR (month) = ET_L (month) – P_e (month)

where

ET_L (month) = landscape evapo-transpiration over a month
P_e (month) = effectiveness factor x rainfall over a month
Table 1-10: Effective rainfall values for different soil types and root zone depths

<table>
<thead>
<tr>
<th>Root zone depth (mm)</th>
<th>150</th>
<th>300</th>
<th>450</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average monthly effective rainfall</strong>&lt;br&gt;(expressed as % total monthly rainfall)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>44</td>
<td>48</td>
<td>52</td>
<td>55</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>47</td>
<td>53</td>
<td>58</td>
<td>63</td>
</tr>
<tr>
<td>Loam</td>
<td>49</td>
<td>57</td>
<td>63</td>
<td>68</td>
</tr>
<tr>
<td>Clay loam</td>
<td>47</td>
<td>55</td>
<td>60</td>
<td>65</td>
</tr>
<tr>
<td>Clay</td>
<td>45</td>
<td>51</td>
<td>55</td>
<td>59</td>
</tr>
</tbody>
</table>

*Source: McCabe 2005*

This version of the landscape coefficient method is recommended in:

- McCabe (2005), a guideline document for *Landscape Irrigation Scheduling and Water Management* prepared by the Water Management Committee of the Irrigation Association (of USA); and

This approach to estimating landscape water requirements has several limitations which make it unsuitable for developing irrigation budgets intended to advance the objectives of sustainable water use and water demand management on urban landscapes:

- The landscape coefficients are almost entirely subjective with, at best, limited data to justify most of them, and no work has been undertaken to evaluate the consequences of incorrect estimates (Costello et al. 2000).
- Although the model takes account of rainfall, it is achieved by considering rainfall as a discrete variable on a monthly scale. This scale is too coarse to maximise the estimate of the irrigation budget. This is because a monthly water balance ignores the soil water storage, which is influenced on a day-to-day basis by daily rainfall and evapo-transpiration, and which in turn influences the amount of water that needs to be externally supplied to the plant as irrigation (Yellamanda 1995).
1.3.4 Australian method for irrigation requirement of public open spaces

A method similar to the landscape coefficient method has been developed in South Australia for estimating irrigation budgets and evaluating the performance of turf and sporting grounds (Charlton 2005). This approach is recommended in the Code of Practice for Irrigating Public Open Spaces published by collaboration between South Australian (SA) Water and SA Local Government.

This Australian method makes use of a crop factor (CF), a coefficient to be used in conjunction with pan evaporation. Pan evaporation is a measure of evaporation estimated from the water lost into the atmosphere from an open surface of water. This is unlike evapotranspiration which is a measurement of water lost to atmosphere from an open homogeneous field of a single crop. As with the crop coefficient, crop factor values are well established for turf grasses. In addition to crop factor, a coefficient called the turf quality visual standard index (TQVSI) factor is applied to pan evaporation. The rationale behind using a TQVSI factor is that the amount of irrigation water depends on the quality of turf that is required for the turf ground which, in turn, depends on the purpose for which the ground is used. Accordingly, there are four classifications of TQVSI (Table 1-11) that can be assigned to a given turf ground, depending on its function. Hence, according to this method, the LWR for a turf area is estimated as follows:

\[
LWR_{(month)} = ET_L_{(month)} - P_e_{(month)}
\]

where

\[
P_e_{(month)} = \text{effectiveness factor} \times \text{rainfall over a month or a quarter; effectiveness factor varies between 0.4–0.7}
\]

\[
ET_L_{(month)} = \text{landscape evapo-transpiration over a month or a quarter}
= CF \times TQVSI \text{ factor} \times E_{\text{pan}}_{(month)}
\]

where

\[
E_{\text{pan}}_{(month)} = \text{pan evaporation for the month}
\]
This approach takes account of rainfall and the amenity level that will influence the turf water requirement. The TQVSI factor provides some scope for conserving the water, as the estimate of turf water requirement is commensurate with the level of activity to which the turf is going to be subjected. The limitations of this approach are that: a) it is restricted to estimating the water requirement for turf; and b) the method does not differentiate between turf grown on sandy soil and turf grown on clayey soil.

1.3.5 Limitations of current approach

The limitations of the empirical methods can result in over-watering or under-watering of urban landscapes. In addition to the waste of water, negative impacts of over-watering include (Kirkham 2005):

- drainage losses resulting from excessive irrigation which, in places such as the Sydney region, can contribute to secondary salinity;
• the discharge of pollutants to the water bodies from the runoff or drainage from the landscapes owing to the presence of fertilisers and pesticides carried by the drainage and runoff water.

On the other hand, under-watering can result in undesirable landscape outcomes in the form of poor health and appearance.

There is thus a need to develop a rational approach that can provide an estimate of the landscape water requirements that responds to most of the physical variables or parameters of a site, does not overestimate the requirements, and thereby serves the purpose of water demand management, by:

• taking account of rainfall;
• taking account of the root zone depths of different vegetation types and how well those plant types can access the water stored at root zone depth, especially during dry periods (of no rainfall);
• taking account of soil water balance; and
• incorporating a daily water balance, rather than a monthly balance.

This will result in more realistic estimates of irrigation water requirements with the added advantage of estimating losses from a given irrigation rate and thereby managing drainage losses through improved water use efficiency.

Table 1-12 gives a comparative view of the various methods of estimating landscape irrigation water requirement.
Table 1-12: A comparison of the methods for estimating irrigation water requirement of urban landscape

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Evapo-transpiration</td>
<td>yes</td>
<td>yes</td>
<td>yes*</td>
<td>yes</td>
</tr>
<tr>
<td>Rainfall</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Soil type</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Water use characteristics of plant</td>
<td>yes</td>
<td>yes</td>
<td>yes (but limited to turf only)</td>
<td>yes</td>
</tr>
<tr>
<td>Root zone depth</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Microclimate</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Planting density</td>
<td>yes</td>
<td>yes</td>
<td>yes*</td>
<td>yes</td>
</tr>
<tr>
<td>Daily water balance</td>
<td>no (monthly)</td>
<td>no (monthly)</td>
<td>no (monthly)</td>
<td>yes</td>
</tr>
</tbody>
</table>

**Notes:**

* makes use of pan evaporation instead of evapo-transpiration
+ makes use of *turf visual quality index* values for premium lush, moderate and strong growth and for low maintenance

### 1.4 Way forward

The review of the state of urban irrigation demand management revealed a need for applying the end-use analysis approach to outdoor water use; and for developing appropriate methods for estimating the bio-physical water requirement of urban landscapes.

A review of the existing methods for estimation of irrigation water requirement of urban landscapes revealed the limitations of the existing methods and a need for developing a rational method that takes account of the characteristics of the soil, climate, plant type, landscape composition (distribution of turf and non-turf areas) associated with the urban landscape.
Hence, as a way forward, the thesis poses the following questions with respect to urban irrigation (outdoor) demand:

i) How can the end-use analysis approach be applied to analyse urban irrigation demand at a regional scale?

ii) How can the end-use analysis approach incorporate a rational method of estimating the optimum amount of irrigation water required to maintain a domestic garden within a given soil-climate zone which, when compared to the actual outdoor water use, will help estimate and quantify the water-saving potential that exists in urban landscapes?

In answer to the first question, the thesis proposes to apply end-use analysis to urban irrigation end-use, as shown in Figure 1-1 below. In this approach, a given urban region is first broken down into zones that share similar types of soil and climate. Individual soil–climate zones are then disaggregated into different kinds of landscapes or green spaces that contribute to the irrigation demand. This is done because irrigation demand is influenced not only by the type of urban landscape but also the purpose for which the green space has been provided.

Hence, within a soil–climate zone, active recreation green spaces like golf courses and soccer fields would have different levels of water demand as compared to passive recreation parks and domestic gardens in the same zone. The irrigation water requirement for each type of green space is then modelled by taking account of the individual planting types that constitute the particular landscape type.
In answer to the second question, the thesis proposes:

- Defining and using two key concepts in the context of urban irrigation demand management. One of them is *landscape irrigation budget*, which is defined as the minimum irrigation water requirement (for a given period: month or quarter) to maintain an urban landscape with given soil, climate, plant and landscape characteristics, in reasonable health and appearance. The second concept is that of the *water-saving potential* of urban landscapes. It is defined as the difference between water actually applied to the landscape and the irrigation budget of the landscape.
- A framework called the WASP framework, which incorporates the two concepts, and is shown in Figure 1-2. The acronym WASP when referring to the framework stands for the Water-Atmosphere-Soil-Plant interactions that are modelled in its first module (Module 1) and the Water Saving Potential (WaSP) that is estimated in its second module (Module 2). WASP Module 1 incorporates a rational model to estimate the landscape irrigation demand.
budget. It makes use of data related to soil, climate and landscape characteristics. WASP Module 2 estimates the water-saving potential of the urban landscapes being analysed by noting the difference between the landscape irrigation budget (estimated by Module 1) and the irrigation actually applied, estimated from the metered consumption data of the landscaped properties. Such a framework would help in removing the element of guesswork from the determination of demand management potential that may exist across existing green spaces within an urban region. The framework can therefore be used by urban water planners and managers to develop urban irrigation demand management programs that have a scientific rationale and are better informed and better targeted than current outdoor demand management programs.

Figure 1-2: Proposed WASP framework for facilitating urban irrigation demand management
1.5 Research aims and objectives

The research aims to apply the concepts of landscape irrigation budget and water-saving potential for facilitating and supporting demand management of urban irrigation using domestic gardens located in the local government areas (LGA) namely, Kogarah and Penrith (in the Sydney Metropolitan Area) in New South Wales, Australia, representing two different soil-climate zones.

A domestic garden was selected as the case study because it is the most complex landscape when compared with other urban landscapes, with respect to its planting composition, water demand, characterisation and distribution across the urban region. In comparison to the domestic garden, other urban landscapes such as public parks, recreation grounds, sporting ovals and golf courses are relatively simpler in their planting composition and characterisation. However, the framework developed in the thesis can be easily used and extended to analyse the irrigation demand of these other urban landscapes.

The research has the following objectives to facilitate the application of ‘end use analysis’ approach to analysis of urban irrigation demand and development of outdoor demand management policies and programs:

1. To develop a rational approach to estimating irrigation water requirement or landscape irrigation budget.
2. To characterise the case study domestic gardens from Penrith LGA and Kogarah LGA.
3. To develop landscape irrigation budgets for the case study gardens.
4. To estimate the water-saving potential of the case study gardens.
5. To evaluate the effectiveness of water restrictions in achieving reduction in urban irrigation demand of the case study gardens.

1.6 Chapters ahead

The thesis is structured in the form of eight chapters, including this current chapter.
Chapter 1: Introduction and Literature Review  The current chapter introduced the research problem and the background to urban water demand along with a review of the state of urban irrigation (outdoor) demand management. A review was presented of the available methods to estimate landscape irrigation water requirement. Following the two reviews, the chapter highlighted the gaps in the knowledge and outlined how the research proposes to address these gaps.

Chapter 2: Research Methodology  This chapter describes the methodology and approach adopted to address each of the research objectives, and the methods which were employed for the research.

Chapter 3: Development of Rational Approach to Estimating Landscape Irrigation Water Requirement  In this chapter, a rational approach to estimating landscape irrigation water requirement is developed. The rational approach has been developed in the form of a modelling framework; hence the description includes discussion on the basic assumptions involved along with explanations of the algorithms and equations used. The discussion is followed by application of the rational method to estimate the irrigation water requirement for turf, shrubs and trees in clayey and sandy soil, and by a sensitivity analysis of the various independent variables which are used as input parameters.

Chapter 4: Characterisation of Domestic Gardens  The first step in the application of WASP, the proposed policy framework, was to characterise the urban landscapes (domestic gardens in the case of this thesis) whose irrigation budget and water-saving potential is to be determined. Hence, this chapter describes how the domestic garden sites were selected and characterised by analysing geo-coded aerial photographs and physically visiting a sample of the domestic gardens from each local government area. The characterisation was aimed at determining the area characteristics, micro-climate characteristics and water use characteristics as noted by the plant composition of the domestic gardens.

Chapter 5: Development of Landscape Irrigation Budget for Domestic Gardens in Kogarah and Penrith  This chapter describes how the rational approach that was developed in Chapter 3 was applied to the case study domestic gardens in Kogarah and Penrith LGAs to develop a landscape irrigation budget for nine different garden scenarios that can be created from a combination of microclimate and water use characteristics of domestic gardens. The chapter
also presents a comparison of the irrigation budgets using conventional empirical methods with the irrigation budgets developed using the rational approach proposed in the thesis. The aim of presenting the comparison is to demonstrate why a rational approach to irrigation budget estimation is critical to setting any policy objectives for outdoor water demand management.

Chapter 6: Water-Saving Potential of Domestic Gardens in Kogarah and Penrith This chapter describes how Module 2 of the proposed WASP framework was applied to the case study domestic garden sites in Kogarah and Penrith to estimate their water-saving potential and to evaluate the effectiveness of water restrictions that have been in place for the five years since 2002.

Chapter 7: Discussion This chapter discusses the results of undertaking ‘end use analysis’ of urban irrigation demand in the context of the broader literature with the view of demonstrating how the research findings advance the knowledge of urban irrigation demand management.

Chapter 8: Conclusion This final chapter of the thesis presents a critical summary of the research findings while also stating their limitations and how they may be addressed in future research.
2. Research Methods

2.1 Site description

This chapter describes the research methodology that was used to achieve the following research objectives with respect to domestic gardens located in two local government areas within the Sydney Metropolitan Area:

- development of rational method of estimating landscape irrigation budget.
- landscape characterisation
- estimation of landscape irrigation budget
- estimation of water saving potential before and after water restrictions.

This section describes the characteristic features of the two local government areas namely, Kogarah and Penrith, in Sydney (Australia), where the domestic garden sites studied for the research are located.
2.1.1 Geographic location

As shown in Figure 2-1, Kogarah and Penrith are two local government areas (LGA) of Sydney, a metropolis located in east-central New South Wales, Australia. Kogarah LGA is located in the southern suburbs, about 15 kilometres from the Sydney central business district, at sea level, at latitude 33° 54' 03" S and longitude 151° 06' 2" E. It is bounded by Hurstville City in the north-west and west, Rockdale City in the north-east and east and the Georges River in the south). The Kogarah LGA is predominantly residential, with some commercial and industrial areas. Kogarah encompasses a total land area of about 20 square kilometres, including waterways and large areas of open space, mainly along the Georges River (Kogarah Council 2008).
Penrith local government area is a city on the western fringe of the Sydney metropolitan area. Penrith is approximately 54 kilometres by road west of the CBD, 30 metres above sea level, and is located at latitude 33° 45' 01" S and longitude 150° 41' 39" E. The local government boundaries of the City of Penrith encompass an area of approximately 407 square kilometres on the Nepean River flats of the Cumberland Plain. The Blue Mountains rise at the western border (Penrith City Council 2008).

### 2.1.2 Weather features

The climate station nearest to the Kogarah LGA is located at Sydney Airport and is operated by the Bureau of Meteorology. The 100 year (1905-2004) average annual rainfall is approximately 1061 millimetres. On average, more rain falls between January and June and less rain falls between July and December. Highest annual rainfall (which occurs during February-March) is about two times the lowest annual rainfall (which occurs during August-September). The temperature ranges for warmest and coolest months for Kogarah are 19-26 degree Celsius and 7-17 degree Celsius respectively (Bureau of Meteorology, 2009a).

Much of the Penrith local government area lies in a low rainfall area, with a 100 year (1905-2004) average of 799 mm per annum. Highest annual rainfall during February-March is about four times the lowest rainfall during August-September. The climate here is usually more extreme than in nearby temperate metropolitan Sydney, the flat plains country being exposed to frosts in winter and severe heat in summer. The temperature ranges for warmest and coolest months for Penrith are 18-38 degree Celsius and 5-18 degree Celsius respectively (Bureau of Meteorology, 2009b).

### 2.1.3 Housing stock

According to the 2006 Australian Census, single detached dwellings (also known as separate houses) constituted about 59% of the total dwelling structures in the Kogarah LGA—about 11,000 single detached dwellings (Kogarah Council 2008). In Penrith, about 48,500 separate houses constituted 85% of the total number of dwellings (Penrith City Council 2008). Thus, Penrith has almost five times the number of separate houses than Kogarah. This has implications with respect to opportunities for water savings, which are likely to be more where the number of houses is greater.
2.1.4 Soil characteristics
Kogarah LGA is located on a region of Hawkesbury sandstone, and has shallow sandstone-derived soils with predominantly sandy subsoils (Kogarah Council 2008). Penrith is located on the Cumberland Plain where the soils are frequently alluvial in type, shale-derived clay soils, typically clay loam or loamy topsoil overlying clay subsoils (Penrith City Council 2008).

2.2 Research Methodology
As the research aim was to demonstrate that the proposed framework (WASP) has the capacity to facilitate urban irrigation demand management, it was used as the research methodology.

Figure 2-2 outlines the research objectives and methods entailed in the research methodology, which is based on the two key concepts of landscape irrigation budget and landscape water saving potential.

Having defined the two concepts (see Chapter 1, section 1.4), there were five research objectives. The first research objective was to develop a rational method of estimating the landscape irrigation budget that could be applied to domestic gardens in general, and to the case study domestic garden sites in particular. This objective involved undertaking a literature review of the methods that are currently used for estimating irrigation water requirements of urban green spaces such as large turf areas, sporting fields and golf courses. Understanding the limitations of the current methods, which do not well serve the objective of irrigating with the view of managing the irrigation demand, a rational approach was developed to estimate the landscape irrigation budget for domestic gardens. The rational approach involved conceptualising a biophysical model and writing algorithms and equations that took account of the factors that have a direct influence on the water requirements of domestic gardens. These factors included: soil properties, macro-climate, micro-climate, and the water use and plant characteristics of landscape plantings. The rational method, thus developed, is incorporated as Module 1 in the WASP Framework (Error! Reference source not found.), and is henceforth referred to as WASP Module 1.
The second research objective of landscape characterisation was achieved by undertaking a survey of the case study domestic garden sites in the suburbs of Kogarah LGA and Penrith LGA. The survey involved: a) physically visiting selected domestic gardens in both LGAs; and b) observing and analysing the aerial photographs of the properties where the case study sites were located. The survey was undertaken with a view to study those characteristics of a domestic garden that influence the volume of water required to maintain it in a reasonable health and appearance. The features that were studied to help characterise the gardens included:

1. landscape size and layout
2. shrub: turf ratio
3. predominant planting types and their water-use characteristics; their planting density
4. micro-climate to which the gardens were exposed.

The third research objective involved applying the rational method (WASP Module 1) to develop landscape irrigation budgets for the case study domestic garden sites. Irrigation budgets were developed for nine scenarios, as shown in Error! Reference source not found. Each budget was developed on a quarterly basis using 100 years (1906-2005) of daily weather data. WASP Module 1 estimated the irrigation budget by simulating the interactions taking place between soil, plant and atmosphere, and is expressed in millimetres (mm) of irrigation water required for each quarter.
RESEARCH AIM
To demonstrate the development and application of WASP policy framework for sustainable urban irrigation

Research Objectives
To develop and apply the following key elements of WASP

- Development of rational method of estimating landscape irrigation budget (1)
- Characterisation of domestic gardens (2)
- Estimation of landscape irrigation budget for case study gardens (3)
- Estimation of WASP and evaluation of water restrictions (4)

RESEARCH METHODOLOGY
Using suburban domestic gardens as case study, undertake

- Literature review and biophysical modelling (1)
- Survey of domestic gardens (2)
- Biophysical modelling WASP Module 1 (3)
- Water demand modelling WASP Module-2 (4)

Research Methods

- Review current methods of estimating irrigation budget.
- Develop a daily water balance
- Garden visits
- Analysis of aerial photos using GIS
- Run the rational bio-physical model for 100 years of daily weather data.
- Identify landscape scenarios.
- Estimate irrigation budgets for landscape scenarios.
- Create a demand model to estimate garden irrigation consumption from metered consumption data.
- Estimate WaSP by comparing actual irrigation applied with irrigation budget.
- Compare WaSP before and after restrictions.

Figure 2-2: Research aim, objectives, methodology and methods
The fourth research objective was to estimate the water saving potential of the case study sites in the two LGAs. This involved water demand modelling, with the objectives of: a) obtaining an indoor and outdoor (garden) water use breakdown of the quarterly metered water consumption data of the case study properties as proportions of total household water use; b) converting the volumetric outdoor consumption to mm of applied irrigation by dividing the volume of water by landscape area, as estimated during landscape characterisation; and c) calculating the difference between mm of applied irrigation and mm of irrigation budget as an estimate of water saving potential of each of the case study sites. The fifth research objective was to evaluate the effectiveness of water restrictions as demand with respect to achieving the reduction in demand management potential. Hence, this was estimated by noting the difference between the water saving potential of case study sites for periods before and after water restrictions.

Sections 2.2 to 2.5 describe in detail the methods adopted for achieving each of the four stated research objectives.
2.3 Biophysical modelling of landscape irrigation water need

A literature review was undertaken of the current methods to estimate the landscape irrigation water requirement as used by commercial urban irrigators for scheduling irrigation systems on large turf areas, sporting fields and golf courses. The review revealed the following limitations in the methods currently in use:

- They were empirical in nature and thus did not take account of all the major factors that influence the amount of irrigation water required to maintain the garden plant.
- Not taking account of the root zone depth of the plants being watered meant the methods did not differentiate between the amount of water required by turf and the amount required by shrubs.
- Not taking account of the soil properties of the gardens being watered resulted in the methods arriving at the same irrigation water requirements for gardens sited on sandy soil and on clayey soil. This resulted in overwatering of gardens on clayey soil.

The above listed limitations justified the need to develop a more rational method that would meet the objective of managing outdoor water use by optimising the amount of water applied on domestic gardens.

The biophysical modelling used here for estimating the landscape irrigation budget of a domestic garden site is based on the soil water balance approach commonly adopted in irrigated agriculture (Kirkham 2005) and the landscape coefficient approach as developed by Costello et al. (2000) for estimating the water requirements of an urban landscape. The rational method so developed involves:

- breaking down the landscape into its individual plant components which in the case of a domestic garden typically include turf, groundcover, shrubs and trees (Figure 2-4);
- estimating irrigation water requirement for individual components;
• estimating the irrigation water requirement for the entire landscape as the weighted average of the requirements of individual components, the weighting factor being the canopy area of individual planting component relative to the total area of landscape.

This conceptualization of an urban landscape assumes that individual landscape components to be acting independent of one another, which is contrary to reality. As in reality the landscape components often occupy the same soil space and therefore may either compete or share the water stored in their common soil zone, depending upon the location and dimensions of their root zone depths. This will result in either increasing or decreasing the irrigation water required by the landscape as a whole. However, keeping the model simple was the main aim of disregarding this complexity.

Figure 2-4: Breakdown of domestic garden landscape by its plant components for estimation of landscape irrigation budget

2.4 Landscape survey

Two methods were employed for surveying domestic garden sites in Kogarah and Penrith with the view of characterising them for the case study:

• garden visits
• analysis of aerial photographs of the gardens.
A total of 222 domestic gardens were surveyed in Kogarah LGA using aerial photographs; physical visits were made to nineteen of them. In Penrith, 192 domestic gardens were surveyed using aerial photographs; physical visits were made to twenty of them. The relative locations of the gardens surveyed in Kogarah and Penrith are shown in Figure 2-5 and Figure 2-6 respectively.

The following subsections describe:

- how the gardens were selected for survey by garden visit and for survey using aerial photographs
- details of the method of garden visit that was employed for landscape survey
- details of the method of landscape survey that made use of aerial photographs of the gardens
- how the data collected from two different methods was analysed.

2.4.1 Selection of domestic gardens for the landscape survey
A flyer (see Appendix 1) inviting householders to participate in a garden survey was dropped in the letterboxes of randomly selected houses within each LGA. Visits were made to the gardens of those who responded in favour of the invitation. Following the response received from the letterbox drops, nineteen domestic gardens were visited in Kogarah LGA and twenty domestic gardens in Penrith LGA.

For surveying the gardens using aerial photographs, eight to ten houses were selected in the neighbourhood of each household that participated in the survey by garden visit, including the aerial photo of the garden visited. This approach was taken because the predominant water-use characteristics of the landscape, which could not be studied through aerial photography but could be studied for each garden visited, was assumed to apply to the gardens in its neighbourhood and adjoining it. This assumption is a major limitation of the methodology particularly in the absence of a comprehensive survey of domestic gardens that can provide evidence of the water use characteristics of predominant plant species in the suburb being studied. However, the assumption is not unreasonable because it is not unusual to find a finite selection of plants that tend to grow better in a given soil-climate zone and therefore to be predominantly found in the domestic gardens of a given suburb.
This resulted in a total number of 222 domestic gardens surveyed by aerial photographs in Kogarah, and 192 in Penrith.

Figure 2-5: Relative location of domestic gardens surveyed in Kogarah LGA

Figure 2-6: Relative location of domestic gardens surveyed in Penrith LGA
2.4.2 Method of garden visit
The garden visit involved visiting the front yard and back yard of the house, after making an appointment with the home owner. A pre-designed survey form (see Appendix 2) was used to record measurements and observations of the characteristics of the landscape. The recordings pertaining to garden characteristics included:

1. **Dimensions of turf areas and non-turf planted areas (garden beds)**
   Measurements were taken of the turf area and other planted areas by the method of ‘pacing’. Each pace was equal to 0.75 m.

2. **Percentage breakdown of non-turf planted area by shrubs and ground cover**
   Approximate percentage of distribution of shrubs and ground covers in the non-turf planted area was noted by observation and recorded in the survey form. Where beds of shrubs and groundcovers were distinctly separate, the percentage breakdown was estimated from the areas of their respective garden beds.

3. **Tree canopy size**
   This was noted by observation. Based on the size of the canopy, the tree size was recorded as:
   - S when canopy size was < 1 metre
   - M when canopy size was 1–3 metres
   - L when canopy size was > 3 metres.

4. **Type of turf; names (botanical or common) of trees, shrubs and ground covers in the garden and their water-use characteristics**
   These recordings were made with help from a horticulturist who took part in the garden visits. This involved identifying the botanical and/or common names of the turf and other plantings and recording them in the survey form. Water-use characteristics of each planting were confirmed by referring to the Plant Selector database available on the website of the Sydney Water Corporation ([www.sydneywater.com.au/WaterSaving/PlantSelector/](http://www.sydneywater.com.au/WaterSaving/PlantSelector/)). The SWC database identifies about 950 plant species, providing descriptions of them along with their water-use characteristics, identified visually by one, two
or three water drops, indicating low water use (one drop), moderate (two drops) and high (three drops).

5. **Microclimate factor (K\textsubscript{mc})**

The microclimate factor, K\textsubscript{mc}, was noted by observation. Based on the extent of exposure of the plants in the garden to full sun and/or heat radiation from a hard surface (such as road, paved area, concrete or brick wall) in close proximity, K\textsubscript{mc} was recorded for trees, shrubs and ground covers as (Costello et al. 2000):

- H (high) when 50% or more of the garden area was exposed to full sun or afternoon sun for a good part of the day or in the proximity of a hard surface that was exposed to full sun or afternoon sun for a good part of the day
- M (moderate) when 50% or more of the garden area was exposed to part sun/shade or morning sun for a good part of the day
- L (low) when 50% or more of the garden area was in full shade for a good part of the day

6. **Planting density factor (K\textsubscript{d})**

The planting density factor K\textsubscript{d} was noted by observation. Based on the extent of plant cover, K\textsubscript{d} was recorded for trees, shrubs and ground cover as (Costello et al. 2000):

- H (high) when there was no empty space or exposed soil in the plant bed
- M (moderate) when the spacing between the plants or area of exposed soil was less than the canopy size of the plants in the plant bed
- L (low) when the spacing between the plants or area of soil exposed was equal to or more than the canopy size of the plants in the plant bed.

**Assigning planting density and microclimate factors, in practice**

Figure 2-7, Figure 2-8 and Figure 2-9 show examples of assigning planting density and microclimate factors to the irrigation zones within a landscape.
Figure 2-7: Example 1: Assigning planting density factor and microclimate factor. Owing to the high planting density in the garden bed, planting density factor $K_d$ is assigned as H for high; the microclimate factor $K_{mc}$ is assigned as M for medium, as the bed is exposed to part sun and part shade for a good part of the day.
Figure 2-8: Example 2: Assigning planting density factor and microclimate factor. As the planting density in the garden bed is medium, the density factor $K_d$ is assigned as $M$; the bed is in shade for a good part of the day, so the microclimate factor $K_{mc}$ is assigned as $L$ for low.

Figure 2-9: Example 3: Assigning planting density factor and microclimate factor. Here the planting density in the garden bed is low, so the density factor $K_d$ is assigned as $L$; as the bed is in full sun and close to the brick wall for a good part of the day, the microclimate factor $K_{mc}$ is assigned as $H$ for high.

2.4.3 Using aerial photographs for landscape survey
As illustrated by Figure 2-10 and Figure 2-11, the property that was surveyed by garden visit, along with eight to ten houses adjoining and in the neighbourhood, were selected for landscape characterisation through examination of aerial photographs obtained from Kogarah Council and Penrith City Council, respectively. Local councils tend to update aerial photographs of the area under their supervision once every two or three years, and the historical photos from the previous version then become available from the archives. For the purpose of characterising landscapes for this research, with a view to comparing the actual water applied with the irrigation budget, photographs were requested for the most recent year when water restrictions did not apply (1997–2002).³ Metered water consumption data for these properties were being sought from Sydney Water Corporation for the same period. In both cases

³ Water restrictions have been enforced in Sydney since 2003 in the following sequence: Level 1: 1 October 2003 to 31 May 2004; Level 2: 1 June 2004 to 31 May 2005; Level 3: 1 June 2005 to present.
the oldest aerial photos available from the period of no water restrictions were from 2001.

Each garden from each of the photo patches was analysed for the following characteristics relevant for the purpose of estimating landscape water requirement:

- total area of landscape (back yard and front yard)
- area of garden beds
- turf area
- canopy area of the trees
- planting density of the garden beds
- microclimate to which the garden was exposed.

Figure 2-10: A patch of aerial photos showing the domestic garden inspected at 4 Marsh Place, Cranebrook, Penrith, and the domestic gardens in the neighbourhood that were analysed from aerial photos alone. Corresponding to the twenty domestic gardens visited in Penrith were twenty patches of aerial photos which encompassed a total of 213 gardens that were analysed for landscape characterisation.

The aerial photographs of the properties made available by the councils for the research were geo-coded through the Geographical Information System (GIS)
software program called MapInfo®. This was helpful in undertaking the following tasks that contributed to the analysis of the photos:

- marking out selected areas within a domestic garden, such as turf area, garden beds, tree canopies;
- measuring and estimating the marked out areas and tabulating the data, for later analysis and manipulation in spreadsheets;
- observing the landscape by zooming in and noting the difference in the vegetation.

Figure 2-11: A patch of aerial photos showing the domestic garden visited at 13 Judd Street, Oatley in Kogarah LGA, and the domestic gardens in the neighbourhood that were analysed from aerial photos alone. Corresponding to nineteen domestic gardens visited in Kogarah, nineteen patches of aerial photos encompassing a total of 222 gardens were analysed for landscape characterisation.

2.4.4 Data analysis
The data collected on the survey forms during the garden visits was analysed to ascertain the following characteristics of the garden landscape:
• relative distribution of shrubs and ground covers by their water-using characteristics, i.e. low, moderate or high
• range of planting density
• range of microclimate factors
• range of turf to garden bed ratio
• range of tree canopy sizes
• range of turf areas and garden bed areas.

From the 2001 aerial photographs, the characteristics that were gleaned about the domestic gardens were same as those analysed from the garden visit, except for the information on the relative distribution of the planting types with respect to their water use characteristics. The other difference was that greater numbers of landscapes were analysed using the aerial photos than from the garden visits. The analysis of aerial photos was aimed at determining: the range of planting density, the range of microclimate factors, the range of turf to garden bed ratio; the range of tree canopy sizes, and the range of turf areas and garden bed areas.

2.5 Application of WASP Module 1

The methods involved in the analysis of the data were:

1. Creating a daily water balance model for estimating the irrigation water requirement for individual plant component. Model development is discussed in detail in Chapter 4.
2. Estimating the irrigation water requirement for individual plant components of a domestic garden corresponding to the daily weather data over 100 years (1906–2005) for different combinations of microclimate and water use characteristics.
3. Using the monthly median irrigation water requirement values of plant components to estimate the monthly irrigation budgets for the nine different landscape types listed in Table 2-1 corresponding to different turf to garden bed ratios.
### Table 2-1: Nine landscape scenarios modelled by WASP Module 1

<table>
<thead>
<tr>
<th>Predominant plant type making the landscape</th>
<th>Low water using (LWU)</th>
<th>Moderate water using (MWU)</th>
<th>High water using (HWU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microclimate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In full sun</td>
<td>LWU landscape in full sun</td>
<td>MWU landscape in full sun</td>
<td>HWU Landscape in Full Sun</td>
</tr>
<tr>
<td>Part sun/shade</td>
<td>LWU landscape in part sun/shade</td>
<td>MWU landscape in part sun/shade</td>
<td>HWU landscape in part sun/shade</td>
</tr>
<tr>
<td>Full shade</td>
<td>LWU landscape in full shade</td>
<td>MWU landscape in full shade</td>
<td>HWU landscape in full shade</td>
</tr>
</tbody>
</table>

Figure 2-12 shows the logical sequence of the methods involved in the biophysical modelling for development of irrigation budgets, along with the data requirements.
Figure 2-12: Logical sequence of the methods and inputs in biophysical modelling for development of landscape irrigation budgets
2.5.1 Input data to WASP Module 1

Input data to the model (Module 1) were in the form of data obtained from landscape characterisation and Bureau of Meteorology records along with assumptions relating to properties and characteristics of soil and plant types:

1. *Weather data*: 100 years of daily data on rainfall and reference evapotranspiration (ET\textsubscript{O}) for Penrith and Kogarah were obtained from the SILO Data Drill division of the Australian Bureau of Meteorology. The SILO Data Drill provides interpolated data for any location in Australia.\(^4\)

2. *Soil and plant properties*: Values for soil properties such as maximum water-holding capacity (the maximum allowable depth to which water can be depleted in a given soil before refilling it by irrigation water, corresponding to the clayey soil of Penrith and the sandy soil of Kogarah) were obtained from literature (Kirkham 2005). Assumptions were also made about the effective root zone depth of individual planting types (turf, ground covers, shrubs, trees), which varied according to the water use characteristic. Low water using plants were assumed to have deeper effective root zones as compared to high water using plants with shallower root depths (Handreck 1993).

3. *Landscape data*: The following data obtained from the analysis of landscape survey data were used as inputs to the model:

   a. predominant water-use characteristics of landscape
   b. predominant microclimate factor of landscape
   c. landscape area
   d. turf area

---

\(^4\) The Data Drill accesses grids of data interpolated from point observations by the Bureau of Meteorology. Interpolations are calculated by splining and kriging techniques. The data in the Data Drill are all synthetic; there are no original meteorological station data left in the calculated grid fields. For original meteorological data, you could use other SILO data or contact the climate section of any of the Bureau of Meteorology's regional offices. However, the Data Drill does have the advantage of being available for anywhere in Australia. The Data Drill provides popular meteorological variables that are useful for agro-meteorological research and modelling, the surfaces are interpolated to .05 degrees spatial resolution (around 5 km). The Data Drill is delivered as an email service provided by the Queensland Department of Natural Resources and Mines (QNR&M). To access the Data Drill, a user must define a point in Australia to an accuracy of 3 minutes, a start and finish year (the same if you only want one year of data), the required format for the meteorological variables, and an email address for the return of the results. Source: [http://www.nrw.qld.gov.au/silo/datadrill/](http://www.nrw.qld.gov.au/silo/datadrill/)
e. area of garden bed
f. ratio of turf area: garden bed area.

Figure 2-13 provides a snapshot of the output of the biophysical modelling process, in the form of a landscape irrigation budget for one of the nine types of landscapes.

![Garden Watering Benchmark for MWU Domestic Garden in Half Sun-Half Shade in Penrith](image)

**Figure 2-13:** A snapshot of output from biophysical modelling (WASP Module 1) displaying quarterly irrigation budget for a moderate water using (MWU) landscape in half sun-half shade corresponding to turf to shrub ratios of 1, 0.5 and 0.

### 2.6 Demand modelling: Application of WASP Module 2

Demand modelling, as encapsulated in WASP Module 2, was used to achieve the research objectives of estimating water saving potential and evaluating the effectiveness of water restrictions in achieving the demand management potential of the domestic gardens surveyed and characterised in Kogarah and Penrith. This involved: a) creating a demand model that estimated, from the quarterly metered consumption data, the mm of water actually applied by the property owners on their gardens; b) estimating the water saving potential of the case study garden sites before water restrictions; and c) estimating the water saving potential of those sites after water restrictions.
2.6.1 Creating a demand model
Creating a demand model involved:

- **Collecting the historical metered water consumption data** of the properties whose domestic gardens were characterised. The metered consumption data represents total volume of water consumed over the billing period. Both LGAs are serviced by Sydney Water Corporation (SWC), which bills the residential water users every quarter, following the financial year calendar. The metered consumption data were obtained for the 295 properties in Kogarah and for 213 properties in Penrith that were characterised using aerial photos. SWC has a mandatory obligation to protect the privacy of individual householders. Therefore, without receiving a written consent of the householders, SWC is unable to provide the metered water consumption data of individual properties. Since it was not possible to seek consent from 400-odd householders, SWC was requested to provide the metered consumption data of two adjoining properties by combining them. This way, the privacy of the individual households was protected and meaningful data was obtained. (If this exercise were being undertaken by the water utility internally, then it would be possible to make use of individual household data.)

The metered data was requested for each of the years 1997–2001, the period when no water restrictions were enforced.

- **Making assumptions:**
  - About quarterly indoor water use (for each of those years) which could then be deducted from total household water use in each quarter to get the outdoor water use;
  - about the proportion of outdoor water use that could be attributed to garden watering.

- **Estimating the actual amount of water applied on the garden:**
  - estimating the kL of water applied on the garden; and then
  - estimating the mm of water applied on the garden, i.e. the volume of water applied relative to the total area of the garden. This
enabled comparison of the water saving potential between landscapes.

More detailed description of the water demand model appears in Chapter 6.

2.7 Estimating the water saving potential

This involved noting the difference between the mm of water applied in each quarter and the quarterly landscape irrigation budget corresponding to the landscape type and turf to garden bed ratio representative of the patch of aerial photos to which the domestic garden belonged. The difference when positive was registered by the model as a water saving potential. Depending on its quantity, the water saving potential was classified as low, moderate or high.

When the amount of water applied was less than the landscape irrigation budget, the water saving potential was considered to be zero. In other words, when the water saving potential returned a negative value, it was registered by the model as zero, or nil water saving potential.

2.8 Evaluating the effectiveness of water restrictions

This involved noting the impact of water restrictions on water saving potential by analysing the historical metered consumption data for the period when water restrictions were enforced with respect to the water saving potential and distribution of gardens.

The next chapter describes how the first research objective that of the development of a rational method for estimating irrigation water requirement was achieved.
3. **Rational Approach to Estimation of Landscape Irrigation Water Requirement**

3.1 Chapter aims

This chapter describes the development of the rational method called WASP Module 1, based on biophysical modelling of soil–plant–water interactions, to estimate the irrigation requirements of the individual components of a domestic garden, namely, turf, shrubs and trees. A graphical presentation of the results obtained is included in the chapter. A sensitivity analysis was undertaken to determine the relative sensitivity of the irrigation water requirement estimates to the various input parameters. Results from the sensitivity analysis are presented and discussed at the end of this chapter.

From Chapter 5 onwards, the various steps involved in the application of the WASP framework to the case study domestic garden sites of Kogarah and Penrith are described and the results obtained in each step discussed. These steps include characterisation of domestic gardens in the two suburbs (Chapter 4), development of irrigation budgets for the case study sites in the two suburbs, using WASP Module 1 (Chapter 5), and estimation of the water saving potential of the case study sites in the two suburbs before and after water restrictions, using WASP Module 2 (Chapter 6).

3.2 Modelling philosophy

As an improvement on and as a substitute for the conventional empirical methods of estimating landscape irrigation requirement, a rational approach called WASP Module 1 was developed by adapting the landscape coefficient method of Costello et al. (2000) to incorporate a simple daily soil water balance. The aim of the new method is to estimate landscape irrigation budgets for domestic gardens and other urban landscapes which can be used as a decision-making tool in the context of policy development for managing water demand for these uses.

Decision-making support tool often entail an element of modelling, either conceptual or empirical. There are many approaches to modelling, ranging from those which are
empirical through to those which draw on complex theory in an attempt to simulate a large number of processes known or thought to be important. Models which are useful for management purposes tend to be simple, as these are more readily understood and accepted, and are less demanding on data for their implementation (McNamara 2007).

The soil–water balance equation used at the heart of WASP Module 1 was kept as simple as possible to reflect known, important soil–water processes and to minimise (if not avoid) non-testable assumptions. A further aim in retaining simplicity was to enable the use of readily available climate and soil data. This includes applications either within this project or beyond it.

There is currently insufficient data available to test the soil–water balance model in diverse urban environments, let alone the landscape coefficients which are used for urban irrigation estimations. The collection of such soil water data was beyond the scope of this project.

Rather, the approach taken was to use a minimum number of parameters and to employ sensitivity analysis to identify those for which more careful definition might be required, through either a more thorough search of the literature or, more likely, specific research following the project. The objective was to develop and evaluate the approach, or framework, which is applied and evaluated in Chapter 5. Beyond this, should water-management authorities wish to adopt the WASP approach, this thesis will provide direction for research, if any, to reliably implement it.

WASP Module 1 was developed as an extension of the crop coefficient models developed by Costello et al. (2000) and McCabe (2005), and is focused on a soil–water balance model that aims to obtain realistic estimates of landscape irrigation requirements. Realistic estimates of landscape irrigation budgets are crucial for facilitating and advancing demand management objectives. This is because a close to real value of a landscape irrigation budget can potentially be used as benchmark against which the water applied on existing landscapes can be compared to estimate the water saving potential (WaSP). Estimation of WaSP also facilitates urban irrigation demand management because it can potentially be used to evaluate policies and programs aimed at managing demand.
WASP Module 1 was developed to incorporate a rational approach and a conceptual framework that:

- takes account of the weather and biophysical factors that influence the irrigation requirement;
- facilitates estimation of irrigation requirements for landscapes located in different soil–climate zones;
- facilitates estimation of irrigation requirements of various landscape types (based on their water-use characteristics) and scenarios (based on the microclimates they may be exposed to).

It must be noted that WASP Module 1 is a modelling framework, a foundation for building a model, and not the model itself. It has been developed to provide a sound basis for a model to be custom built using input data specific to particular soil–climate and landscape combinations and validated by conducting field and/or experimental studies on landscape irrigation, which is beyond the scope of this thesis.

A sensitivity analysis has been undertaken of the parameters used in the modelling framework of WASP Module 1 to understand how each parameter (module input) influences landscape water requirement (module output), thereby providing insight into the need for any further investigation and research to develop more accurate values.
3.3 Fundamental concepts used in a daily soil–water balance

![Diagram of soil–plant–water relationships in the effective root zone](image)

**Figure 3-1: Soil–plant–water relationships in the effective root zone**
Source: McCabe (2005a)

The physical limits to the soil–water balance are defined primarily by the concepts of field capacity (FC) and permanent wilting point (PWP). Figure 3-1 shows a schematic representation of soil water types based on their availability to the plant and their impact on plant stress. The schematic is helpful in understanding the basic concepts that are used in the development of a soil water balance.

### 3.3.1 Field capacity (FC) of soil

The field capacity of a soil is the upper limit of available water for plants. It is the amount of water retained in the soil after irrigation or rain when the rate of downward movement (percolation through the soil) due to gravity has substantially decreased (Kirkham 2005). Any soil water above field capacity may be briefly available, but it cannot be held against the force of gravity and will drain away, thereby becoming inaccessible.
3.3.2 Permanent wilting point (PWP)
The permanent wilting point is the lower limit of available water to a plant, the point at which transpiration effectively ceases. Defining the term from the perspective of soil water, PWP is the amount of water per unit weight or per unit of bulk volume in the soil, expressed as a percentage that is held so tightly by the soil matrix that roots cannot absorb it (Kirkham 2005). The water content below the wilting point cannot be extracted by plant roots.

3.3.3 Effective root zone (RZ)
The effective root zone is the depth of soil from which a plant can draw nutrients and water. The effective root zone is also referred to as the active root zone, or just the root zone. The water that is available to plants for their use lies between field capacity (FC), the upper limit of RZ, and permanent wilting point (PWP), the lower limit.

3.3.4 Potentially available water content (PAWC)
Potentially available water content, or PAWC, expressed in units of depth, is the difference between the water content in the root zone at field capacity and permanent wilting point, over the depth of effective rooting. Total available water is mathematically expressed as follows:

\[
\text{PAWC} = (\text{FC} - \text{PWP}) \times \text{RZ} \quad \text{(FAO 1998)}.
\]

Water is not always equally available to plants between field capacity and permanent wilting point, a condition sometimes referred to as the non-limiting water range (NLWR). NLWR refers to the conditions when the root water uptake and plant growth is limited not by soil water content but because of other soil or plant factors. The upper limit of the non-limiting water range is often characterised as the readily available water (RAW), and is often expressed as a percentage of PAWC.

3.3.5 Readily available water (RAW) or available soil water (ASW)
Readily available water, RAW, is sometimes known as available soil water, ASW. Available soil water is expressed as \( \text{ASW} = p \times \text{PAWC} \), where \( p \) is the average fraction or percentage of PAWC that can be depleted from the root zone before moisture stress reduces ET (FAO 1998). ASW varies not only with soil type, but also...
with the objective of the irrigation manager and the plants being managed; whether to maintain plantings at low stress for enhanced productivity, or whether to allow greater stress, taking advantage of the fact that the plants will survive and maintain the required amenity value with higher water stress. A drought-resistant plant can survive greater soil water depletion than a drought-sensitive plant.

3.3.6 Allowable depletion (AD)
Allowable depletion, AD, is a conceptual soil water depth used to manage an irrigation schedule based on soil water content or the soil–water balance (McCabe 2005). It is the point of maximum depletion, the point at which irrigation water will be applied. For urban landscapes, the refill point varies with the objectives of the manager. To accommodate this variation, the concept of maximum allowable depletion (MAD) is introduced, which is expressed as a varying percentage of PAWC. Thus for urban irrigation, AD is estimated as:

\[
AD = MAD \times PAWC \quad (\text{FAO 1998})
\]

WASP Module 1 computes a cumulative soil water deficit, that is, the difference between the present available soil water (ASW) and the potentially available soil water (PAWC).

3.4 Introducing WASP Module 1

WASP Module 1 uses a simple soil–water balance to first estimate the irrigation requirements for the individual components of an urban landscape. The irrigation water requirement for the entire landscape is then estimated as a weighted average of the requirements of each component, the weighting factor being the area of each component. This section aims to describe the algorithms and assumptions used in estimating the irrigation water requirement of the various components, as they are fundamental to estimating the requirement for the overall landscape. The equation for calculating the landscape irrigation requirement is described in detail in Section 3.7.
3.4.1 Algorithms and assumptions
The soil–water balance of an urban landscape is demonstrated by Figure 3-2 which is a representation of various inputs and outputs within the soil moisture reservoir contained in the effective root zone of the plants in a domestic garden. The WASP Module 1 uses the soil–water balance in this zone to estimate the water that would need to be applied externally in the form of irrigation with a view to maintaining the plants in the garden at the level of amenity required by the manager.

\[
\text{ASW}_1 - \text{ASW}_2 = P + I - (ET + R_o + D)
\]

where

- \( \text{ASW} \) is available soil water at times 1 and 2
- \( \text{ASW}_1 - \text{ASW}_2 \) is the change in soil water during the interval \( t_1 \) to \( t_2 \)
- \( P \) and \( I \) are precipitation and irrigation during this interval
- \( ET \) is evapo-transpiration

Figure 3-2: Schematic representation of landscape components and the daily soil–water balance used in the rational method proposed in the thesis

The soil–water balance can be expressed in various forms (Yellamanda et al. 1995). One that is useful for irrigation studies is:

\[
\text{ASW}_1 - \text{ASW}_2 = P + I - (ET + R_o + D)
\]
• \( R_o \) is surface runoff
• \( D \) is deep percolation (beyond the root zone).

WASP Module 1 makes the following basic assumptions with respect to the soil–water balance, assumptions which are common to development of soil–water balance models (McAneney et al. 1982; Jamieson et al. 1995):

i) All of the rainfall water infiltrates the soil and hence there is no surface runoff.

ii) The soil reservoir responds to water applications by reaching equilibrium instantaneously. The infiltrated water is redistributed uniformly over the effective zone and the water in excess of the corresponding soil storage capacity exits the root zone as deep drainage.

iii) For simplicity, any rainfall that is in excess of field capacity is assumed to result in drainage and is therefore effectively beyond the reach of the active root zone and unavailable to the plants for their growth.

iv) The groundwater table lies well beyond the reach of the roots of the landscape vegetation and hence there is no contribution to soil water from capillary rise.

v) Projected area of the canopy (canopy area) is used in estimating the total irrigation volume, to account for the variation in density of planting of individual landscape components. This is to suit the use of aerial photographs for characterising the landscape. When examining aerial photographs, it is easier to estimate the canopy area than to determine planting density.

The daily soil–water balance equation in WASP Module 1 is an adaptation of the equation used in scheduling irrigation of agricultural crops (McCabe 2005). It can be expressed as follows:

\[
(ASW)_n = ASW_{n-1} + P_n + I_{n-1} - ET_{Ln}
\]

where
Based on the above equation, the daily amount required to be externally supplied to the landscape is determined by the irrigation rule that available soil water (ASW) on any given day should not drop below a fixed value of the maximum ASW, referred to as the potential available soil water (PAW). The lower limit of ASW, when irrigation is triggered, is termed the allowable depletion. The allowable depletion is determined by the type of soil and irrigation management strategy or objective.

**Table 3-1: WASP Module 1: Input parameters and outputs**

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weather parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Daily rainfall</td>
<td>Irrigation water requirement for individual landscape component.</td>
</tr>
<tr>
<td>ET₀</td>
<td></td>
</tr>
<tr>
<td><strong>Soil parameter</strong></td>
<td></td>
</tr>
<tr>
<td>PAWC</td>
<td>Drainage for each landscape component.</td>
</tr>
<tr>
<td><strong>Plant parameter</strong></td>
<td></td>
</tr>
<tr>
<td>Effective root zone depth of landscape components (turf, garden bed plants, trees)</td>
<td>Landscape irrigation water requirement.</td>
</tr>
<tr>
<td><strong>Landscape parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Species factor</td>
<td></td>
</tr>
<tr>
<td>Microclimate</td>
<td></td>
</tr>
<tr>
<td>Plant density factor</td>
<td></td>
</tr>
<tr>
<td><strong>Irrigation management parameter</strong></td>
<td></td>
</tr>
<tr>
<td>Maximum allowable depletion</td>
<td></td>
</tr>
</tbody>
</table>

Based on the inputs and outputs shown earlier in Figure 3-2, the daily soil water balance for a landscape component (turf, garden bed or tree) can be given as:

\[
ASW_n = ASW_{n-1} + P_n + I_{n-1} - ET_{L,n} - D_n \]  \hspace{1cm} (Equation 1)

where
• \( P_n \) is precipitation on day \( n \)
• \( I_{n-1} \) is irrigation applied on the previous day
• \( D_n \) is water lost by deep drainage (includes runoff), resulting from the previous day's precipitation or irrigation. It is estimated on a daily basis when the soil water deficit is negative (i.e. surplus)

This equation can be rewritten in terms of cumulative soil water deficit, as WASP Module 1 compares the cumulative soil water deficit on any day with the refill point. Soil water deficit on the \( n \)th day is the difference between PAWC and the estimated ASW on the \( n \)th day.

Hence cumulative soil water deficit (CWD) on the \( n \)th day is equal to the soil water deficit on the \( n \)th day plus the soil water deficit on the previous day less any irrigation applied on previous day. This can be expressed as:

\[
CWD_n = D + ET_{L(n)} - P_n + CWD_{n-1} - I_{n-1} \quad (Equation \ 2)
\]

where

• \( CWD_n \) is the cumulative soil water deficit on day \( n \)
• \( ET_{L(n)} \) is actual evapo-transpiration on the day

where,

\[
ET_L = K_L \times ET_o = (k_s \times k_{mc}) \times ET_o
\]

where,

\[
ET_o = \text{potential evapo-transpiration on the day}
\]

The cumulative deficit on each day is then compared with the allowable depletion (AD) to determine the amount of irrigation that needs to be applied on the day, if any.

If the cumulative soil water deficit on the day is less than allowable depletion (AD), then no irrigation is applied.
i.e. $I_n = 0$, if $CWD_n < AD$

If the soil water deficit exceeds the allowable depletion, then irrigation is applied to return ASW to PAWC:

i.e. $I_n = CWD_n$, if $CWD_n > AD$
3.5 Module input parameters

3.5.1 Landscape evapo-transpiration

Evapo-transpiration (ET) refers to the combination of two simultaneous processes whereby water is lost from the soil surface by evaporation and from the plant by transpiration. The amount evaporated from the soil is determined by the water that is available for evaporation and by the fraction of solar radiation that reaches the soil surface.

The evaporation fraction tends to decrease as the plant grows and its canopy shades more of the soil. As the plant becomes well developed and further shades the soil, transpiration forms the predominant fraction of the water lost through evapo-transpiration. The partitioning of evapo-transpiration into evaporation and transpiration for an annual crop is plotted against the leaf area per unit surface of soil below it in Figure 3-3. As the graph demonstrates, 100% of ET comes from evaporation in the early plant growth phase.

The evapo-transpiration rate is normally expressed in depth units, comparable to rainfall, that is, millimetres (mm) per unit time. The time unit can be an hour, day, week, month or the entire growing period of the crop. In the case of WASP Module 1, the time unit is one day.

---

5 Evaporation is the process whereby liquid water is converted to water vapour and removed from the evaporating surface. Water evaporates from a variety of surfaces, e.g. lakes, rivers, pavements, soils and wet vegetation (FAO 1998).

6 Transpiration is the vaporisation of liquid water contained in plant tissues and the vapour removal to the atmosphere. Nearly all water taken up by roots is lost by transpiration and only a tiny fraction is used within the plant (FAO 1998).
Reference or potential evapo-transpiration, or ET₀, is a standard developed in irrigated agriculture to estimate evapo-transpiration for a specific crop and growing conditions. It is defined as the evaporation from an extended surface of a (hypothetical) short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always supplied with water (Kirkham 2005).

In WASP Module 1, evapo-transpiration from a landscape is estimated by using a regional measure of reference evapo-transpiration (ET₀), a microclimate factor (kₘₜₖₗ) to adjust ET₀ for the local microclimate,⁷ and a species factor (kₛ) that accounts for the water-using characteristics of the plant species (e.g. high water-using species and low water-using species). For the sake of simplicity in terms of the number of variables to be accounted for, the density factor kₐ is assumed equal to 1 (implying complete ground cover and no scaling of ET₀).

⁷ Although each landscape component may be exposed to different microclimates, for the sake of simplicity, similar microclimate is assumed for all landscape components, when estimating the budget. However, the module has a provision for accounting for different microclimates for each component, if such information were to be available.
Thus, landscape evapo-transpiration, $ET_L$, of a well-watered landscape is estimated as:

$$ET_L = K_L \times ET_o$$

where

$$K_L = k_{mc} \times k_s$$

Table 3-2 shows the range of values that WASP Module 1 assumes for $k_{mc}$ and $k_s$. They are based on those published in Costello et al. (2000), as to date there is no other published work that has better or scientifically tested and validated values on these factors.

**Table 3-2: Values for species factor and microclimate factor used in WASP Module 1**

<table>
<thead>
<tr>
<th></th>
<th>Species factor ($k_s$)</th>
<th>Microclimate factor ($k_{mc}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>High</td>
<td>0.8</td>
<td>1.2</td>
</tr>
</tbody>
</table>

*Source: Adapted from Costello et al. (2000)*

The major assumptions relating to landscape evapo-transpiration are:

- The planting density factor $k_d$ is assumed equal to 1 to represent a moderate planting density condition (Costello et al. 2000). As WASP Module 1 is specifically aimed at developing irrigation budgets for established gardens, it is reasonable to assume moderate or average planting density.

- The $K_L$ value is assumed to be constant for the entire year. Since the module makes use of daily values of reference evapo-transpiration, it does not require the coefficient value to be varied on a daily basis, as is done by Eching and Snyder (2005)\(^8\), when converting monthly reference ET values to daily $ET_L$ values. $K_L$ depends on factors that do not tend to vary on a daily basis, so the assumption is reasonable.

- The landscape is assumed to be well watered, that is, soil moisture is always replenished by irrigation to field capacity as and when the level drops below the level of allowable depletion, and thus maintained in the realm of readily available water. Therefore the landscape ET is not adjusted for water stress.

---

\(^8\) Eching and Snyder (2005) have developed a spreadsheet-based model called LIMP to estimate daily values of landscape coefficient $KL$ from monthly values of $KL$ using a curve fitting technique.
3.5.2 Effective root zone depth

As defined in Section 3.3.3, the effective root zone, RZ (also referred to as active root zone or root zone), is the depth of soil from which plants can draw nutrients and water. The water that is available to the plants for their use is held by the soil within the zone between the upper limit of field capacity (FC) and the lower limit of permanent wilting point (PWP). Effective root zone is not the same as rooting depth, which is the depth of soil where the roots of the plants actually spread, drawing nutrients and water from the soil. Hence, effective root depth tends to be less than the actual rooting depth. Irrigation is managed with the objective of maintaining a specific soil moisture level within the effective root zone, which is influenced by the actual rooting depth of the plant. Thus it is important to understand the active root zone depths of different plant species, soil conditions and the implications of both for plant water requirement.

Rooting depths for a plant species can be determined by observing several soil cores and determining the average depth of root penetration into the soil profile (Weaver 1926). They can also be determined by measuring the changes in soil water content within the root zone. Plants with deep root systems have access to greater reservoirs of water.

Different species are known to access varying proportions of their total water use from different parts of their root zones. Asbjornsen et al. (2007) found that corn and prairie species obtained up to 45% and 36% of their water from the upper 0–20 cm of the soil horizon respectively, while oak trees growing in savannas and woodland obtained up to 40% and 20% of their water from the upper 20 cm, and up to 60% and 80% of their water from depths > 60 cm, respectively. Rooting depths vary widely, dependent on plant species and soil type. Greater rooting depths develop in loose sandy soils than in heavier clayey and/or compacted soils (Schenk and Jackson 2002). In domestic gardens generally, irrigation is managed for turf grass for an effective rooting depth ranging from 120 mm (Symes 2002) to 300 mm (McCabe 2005a). However, maximum rooting depth for turf, both cool-season and warm-season grasses, is known to be in the range of 500–1000 mm (Allen et al. 1998). Figure 3-3 shows the relative root depths of different plant vegetations.
Figure 3-3: Mean and standard error of maximum rooting depth (m) of vegetation by three major functional groups (trees, shrubs and herbaceous plants) and crops
*Source*: Canadell et al. (1996)

Table 3-4: Maximum root depth of common turf grass species

<table>
<thead>
<tr>
<th>Species</th>
<th>Maximum root depth, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kikuyu</td>
<td>2400</td>
</tr>
<tr>
<td>Paspalum and couch</td>
<td>1500</td>
</tr>
<tr>
<td>Buffalo</td>
<td>1000</td>
</tr>
<tr>
<td>Kentucky bluegrass</td>
<td>400</td>
</tr>
<tr>
<td>Bent grasses</td>
<td>350</td>
</tr>
</tbody>
</table>

*Source*: Handreck & Black (1994)
Table 3-4 shows the maximum root depths of common turf grass species. Effective root depths for garden bed plants such as shrubs and ground covers, as assumed by irrigation managers, range from as low as 200 mm (Symes 2002) to 600 mm (Anonymous 2006). The actual rooting depth of shrubs can be much deeper, ranging from 1000 mm to 5000 mm (Seyfried et al. 2005); shrub species from arid zones have roots on the deeper end of the range. Trees tend to have much deeper roots, anywhere from 3000 mm to 10,000 mm (Lefroy and Stirzaker 1999).

Rooting depth has implications for the irrigation schedule as well as for the total volume of irrigation water required over a season to maintain the health and appearance of plants in the domestic garden. As greater rooting depth provides access to a greater volume of readily available water, lower scheduling frequencies can be used for plants having deeper roots. Certain tree, shrub and ground cover species can survive without irrigation in the summer months once they become established (Evans

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9 This is, however, compensated by the amount of refill required which is much greater for deeper root zone species. It also presents a practical issue as the texture of the soil limits the maximum amount of refill that can be applied.
et al. 1996), a feature partially attributable to the deep root zones these species develop.

Rooting depth is also influenced by irrigation and soil management practices (Kirkham 2005). For example, frequent and shallow watering encourages shallow roots, whereas infrequent and deep watering promotes the growth of deep roots. Well-aerated soil tends to promote development of deep roots as it allows and facilitates exploitation of the soil. Soils that are compact and not well aerated tend to result in the development of shallow roots (Handreck 1993).

Table 3-5 shows the effective root zone depths assumed for the plant types in WASP Module 1.

**Table 3-5: Effective root depths assumed in WASP Module 1**

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Depth of effective root zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turf</td>
<td>300-500 mm</td>
</tr>
<tr>
<td>Garden bed plants (shrubs and ground covers)</td>
<td>600-1000 mm</td>
</tr>
<tr>
<td>Trees</td>
<td>2000-3000 mm</td>
</tr>
</tbody>
</table>

Daily soil–water balance (Section 3.4.1) has been investigated in this research, for active root zone depths varying from 150 mm to 5000 mm, to determine the sensitivity of the module output to this particular parameter. The sensitivity analysis is discussed in Section 3.8.

### 3.5.3 Potential available water-holding capacity (PAWC) of the soil

Soil–water balance is a dynamic entity, as removal of water from the soil is continuously occurring due to drainage, evaporation and transpiration, and the addition of water is occurring with rainfall, dew, snow and irrigation (Kirkham 2005). The movement of the water does not cease when there is no addition, but it may continue at a reduced rate for a long time. Thus equilibrium is never reached in practice, and thus FC is not a unique value. However, when undertaking a daily soil–water balance, the saturated level is treated as a quasi-static or non-equilibrium level of moisture at which drainage beyond the root zone is insignificant relative to evapotranspiration (Kirkham 2005).
The maximum potentially available water-holding capacity of a soil (PAWC) is influenced by many factors, the most important of which is soil texture. Kirkham (2005) lists the range of possible factors:

- soil texture and structure
- organic content of the soil
- presence of a watertable closer to the soil surface
- presence of impeding layers or soils having layers of widely differing hydraulic conductivities.

The primary factor accounted for in WASP Module 1 is the soil texture. There are tables readily available that show the expected range of AWC in relation to texture (see Table 3-6 for an example). With respect to other factors, the model assumes that:

- There is no watertable close to the surface of the soil; accessible water tables are generally associated only with low-lying parts of a landscape and in areas with sufficiently high rainfall. These areas are limited in extent in the Sydney region, and are regions identified as being at-risk for secondary salinity. The model would not be applicable to these limited areas; but irrigation-related drainage in nearby high positions in the local landscape may provide the water and mobilise the salt that leads to the risk of salinity where the watertable rises near to the surface. Estimates of drainage made by the model are therefore important for assessing the contribution of irrigation to salinity risk as well as estimating inefficient water use.
- Drainage through the soil profile is limited by the layer of soil with the lowest conductivity or drainage rate. However, for simplicity sake, it has been assumed that there are the soil has a uniform drainage rate throughout the effective root zone depth.
- The rate of extraction of water from the soil by plant roots is uniform in pattern, and therefore the gradients and flow directions in the soil profile and the soil moisture redistribution are also uniform.

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The finer the texture of the soil, the greater is the potential available water-holding capacity (PAWC). Clay soils hold more water at both field capacity and wilting point than sandy soils. Table 3-6 shows typical values of PAWC for different soil types.

**Table 3-6: Potential available water-holding capacity of soils**

<table>
<thead>
<tr>
<th>Soil class</th>
<th>PAWC, mm/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0.17</td>
</tr>
<tr>
<td>Silty clay</td>
<td>0.17</td>
</tr>
<tr>
<td>Clay loam</td>
<td>0.18</td>
</tr>
<tr>
<td>Loam</td>
<td>0.17</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.12</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.08</td>
</tr>
<tr>
<td>Sand</td>
<td>0.06</td>
</tr>
</tbody>
</table>

*Source: McCabe (2005a)*

The PAWC values assumed for the soils of Kogarah and Penrith are shown in Table 3-7.

**Table 3-7: PAWC values of soils predominant in Penrith and Kogarah**

<table>
<thead>
<tr>
<th>Suburb</th>
<th>Soil class</th>
<th>Potential available water-holding capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kogarah</td>
<td>Sand</td>
<td>0.06 mm/mm</td>
</tr>
<tr>
<td>Penrith</td>
<td>Clay to loam</td>
<td>0.17 mm/mm</td>
</tr>
</tbody>
</table>

3.5.4  *Maximum allowable depletion (MAD)*

When plants are water stressed, the rate of evapo-transpiration is reduced in order to conserve water and promote survival under water-limiting conditions (Liua et al. 2005). Rate of ET generally decreases as soil moisture level depletes below field capacity (see Figure 3-4).
In well-watered landscapes, plants do not remain under reduced soil moisture level for long. The MAD for various levels of landscape amenity given in Table 3-8 have been assumed on the basis that, in the case of moderate and low amenity levels, the landscape may experience water stress for a brief period of time.

Table 3-8: MAD values assumed in WASP Module 1

<table>
<thead>
<tr>
<th>Desired landscape amenity level</th>
<th>MAD, % of PAWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (premium, lush green)</td>
<td>20%</td>
</tr>
<tr>
<td>Moderate (strong growth)</td>
<td>50%</td>
</tr>
<tr>
<td>Low (lighter shade of green, lower maintenance, etc.)</td>
<td>70%</td>
</tr>
</tbody>
</table>

3.6 Module outputs

WASP Module 1 estimates daily irrigation water requirement and drainage for individual landscape components. Using these results, overall water requirements for the landscape can be estimated. Section 3.7 following describes how the landscape
irrigation requirement is calculated from the requirements of the individual components.

This section presents the WASP Module 1 outputs in the form of daily irrigation water requirements of individual components of the landscape, which will later be used to estimate *landscape irrigation budgets*. The aim of presenting the module outputs is to examine how they respond to the input variables, and later, in Section 3.8, to undertake a sensitivity analysis of the parameters.

For given daily weather data, soil properties, assumed effective root zone depth, maximum allowable depletion (MAD), $k_{mc}$ factor and irrigation strategy, the module estimates daily irrigation water requirement for each type of plant, along with the daily drainage, which occurs when soil moisture level reaches saturation following a rain event and the excess water exits the root zone to a zone beyond the access of the plant roots.

Any rainfall that exceeds evapo-transpiration after field capacity has been reached is noted as ‘drainage’, without differentiating between the excess rain that will appear as surface runoff and the remaining excess that will end up as drainage. This assumption does not impact on the module’s calculation of the irrigation water required by the plant type and is therefore considered a reasonable assumption. However, the amount of daily drainage calculated in this way would be an over-estimation, as some proportion of the calculated drainage would, in reality, appear as surface runoff.

The outputs obtained for individual landscape components—turf, garden bed plantings, and trees, are presented and discussed in the following sections.

### 3.6.1 Turf: irrigation water requirement and drainage

Figure 3-5 and Figure 3-6 show the daily irrigation water requirement and drainage for turf growing in full sun on sandy soil and clayey soil respectively. The daily rainfall and reference ET for the financial year 1999/2000, for which the module was run, are also plotted in the same graph. The rainfall for the year was 1061 mm;

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As the aim of the analysis was to determine the how the soil and landscape parameters impact upon the irrigation water requirement, the rainfall and weather data was kept constant. Weather data corresponding to Kogarah LGA was used for this analysis.
and the annual average reference ET was 1020 mm. Input parameter assumptions were:

- root zone depth = 300 mm
- available water-holding capacity of sandy soil = 0.06 mm/mm & of clayey soil = 0.17 mm/mm
- $K_L = 0.7$ to represent moderate microclimate and planting density
- maximum allowable depletion = 50% to represent moderate amenity levels.
Figure 3-5: Turf in sandy soil: WASP Module 1 inputs (daily rainfall and ET) and outputs (irrigation water requirement and drainage)
Figure 3-6: Turf in clayey soil: WASP Module 1 inputs (daily rainfall and ET) and outputs (irrigation water requirement and drainage).
Table 3-9: Turf: quarterly and annual irrigation water requirement (mm) and drainage (mm) outputs

<table>
<thead>
<tr>
<th>Turf Input Parameters</th>
<th>Irrigation water requirement, mm</th>
<th>Drainage under the root zone, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root Zone Depth = 500mm; Kl =0.7; Maximum Allowable Depletion = 50%</td>
<td>Turf on Sandy soil (PAWC =0.06mm/mm)</td>
<td>Turf on Sandy soil (PAWC =0.17mm/mm)</td>
</tr>
<tr>
<td>Q1 (July-Sept)</td>
<td>70</td>
<td>27</td>
</tr>
<tr>
<td>Q2 (Oct-Dec)</td>
<td>161</td>
<td>163</td>
</tr>
<tr>
<td>Q3 (Jan-Mar)</td>
<td>194</td>
<td>161</td>
</tr>
<tr>
<td>Q4 (Apr-Jun)</td>
<td>87</td>
<td>52</td>
</tr>
<tr>
<td>Annual</td>
<td>512</td>
<td>402</td>
</tr>
</tbody>
</table>

Table 3-9 presents a summary of quarterly and annual irrigation water requirements and drainage values for turf on sandy and clayey soil, as obtained from the daily run of WASP Module 1 for the rainfall and reference ET data corresponding to the financial year 1999/2000.\(^\text{12}\)

It must be noted that the application rate as high as 75mm may not be practical in one daily session. In reality, the maximum daily irrigation rate applicable on a soil would be limited by the infiltration capacity of the soil and therefore would required to be kept to lower values. This implies that the total amount required (say 75mm) would appear spread across a few days. And, as the aim of the research and the model being developed is to estimate the external water applied with the view to determine the monthly or seasonal benchmark values, an adjustment to account for this practical issue was not considered necessary.

A comparison of the module outputs between the quarters and between the two different soil types shows:

- In both sandy and clayey soils, the irrigation water requirement is relatively less in the winter and autumn quarters (Q1 and Q4) than in the spring and

\(^{12}\) As the aim of the analysis was to determine the how the soil and landscape parameters impact upon the irrigation water requirement, the rainfall and weather data was kept constant. Weather data corresponding to Kogarah LGA was used for this analysis.
summer quarters (Q2 and Q3). The rainfall during Q1 is the lowest, and so also is ET, thus not requiring as much irrigation water requirement as in Q4, when the irrigation water requirement is low on account of high rainfall. Q2 and Q3 are characterised by high ET values, so that even though rainfall is relatively high during these quarters (although not as high as in Q1), the irrigation water requirement is greater.

- The irrigation water requirement is greater in sandy soil than in clayey soil. This is reflective of the greater water-holding capacity of the clayey soil (PAWC = 0.17 for clay as against 0.06 for sand). As the module takes account of the water retained and stored within the soil, the irrigation requirement is influenced by the amount of water stored in the soil on any given day.

- In both sandy and clayey soil, the drainage is lowest during the autumn–winter quarter Q4, which is also the period of lowest rainfall. The drainage is high during quarters Q1 and Q3, which correspond to periods of relatively greater rainfall.

3.6.2 Garden bed: irrigation water requirement and drainage

Figure 3-7 and Figure 3-8 show the daily irrigation water requirement, drainage and soil–water balance for garden bed plants growing in full sun on sandy soil and clayey soil respectively. The daily rainfall and reference ET for the year for which the module was run are plotted in the same graph. The rainfall for the year was 1061 mm; and the annual average reference ET for the same year was 1020 mm.

A comparison of daily plots for turf and garden bed plants shows:

- The maximum level of soil–water balance for garden bed plants is greater than that for turf. This is because the garden bed plants (shrubs and ground covers) have deeper root zone depths than turf, which results in greater depths of soil becoming available for water storage.

- The greater level of soil–water balance in garden bed plants results in lower frequency of irrigation water requirement, although the amount of water required is greater in order to fill the soil to its field capacity, which is greater on account of the deeper root zones.

- The amount of water draining under the root zone of garden bed plants is smaller than in the case of turfs. This also is because of the deeper root zone
depths, which impart the capacity to store relatively greater amounts of water in the soil, effectively reducing the excess that results as drainage.

The irrigation application rate greater than 50mm as estimated by the model (see Figures 3-7, 3-8 for garden bed shrubs and Figure 3-10 for tree in clayey soil) points to the practical issues that is raised by the model assumption. This can be potentially overcome by limiting the maximum irrigation application rate to a value that is practical with respect to the soil type.
Figure 3-7: Garden bed in sandy soil: WASP Module 1 inputs (daily rainfall and ET) and outputs (irrigation water requirement and drainage)
Figure 3.8: Garden bed in clayey soil. WASP Module 1 inputs (daily rainfall and ET) and outputs (irrigation water requirement and drainage).
Table 3-10: Garden bed: quarterly and annual irrigation water requirement (mm) and drainage (mm)

<table>
<thead>
<tr>
<th>Garden Bed Parameters</th>
<th>Irrigation water requirement, mm</th>
<th>Drainage under the root zone, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Garden Bed on Sandy soil (PAWC =0.06mm/mm)</td>
<td>Garden Bed on Clayey soil (PAWC =0.17mm/mm)</td>
</tr>
<tr>
<td>Root Zone Depth = 1000mm; K_L =0.7; Maximum Allowable Depletion = 50%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1 (July-Sept)</td>
<td>31</td>
<td>0</td>
</tr>
<tr>
<td>Q2 (Oct-Dec)</td>
<td>123</td>
<td>86</td>
</tr>
<tr>
<td>Q3 (Jan-Mar)</td>
<td>162</td>
<td>90</td>
</tr>
<tr>
<td>Q4 (Apr-Jun)</td>
<td>61</td>
<td>0</td>
</tr>
<tr>
<td>Annual</td>
<td>378</td>
<td>175</td>
</tr>
</tbody>
</table>

Table 3-10 presents a summary of quarterly and annual irrigation water requirement and drainage values for garden bed plants on sandy and clayey soil, as obtained from the daily run of WASP Module 1 for the weather data for 1999/2000\textsuperscript{13}. A comparison of the module outputs between turf and garden bed shows that:

- While irrigation water requirement per irrigation session is relatively greater in the case of shrubs, the total amount applied over a quarter and over the year is less than that applied to turf. This is true for both sandy soil and clayey soil.
- Garden bed plants in clayey soil do not require any irrigation water during Q1 and Q4, in contrast to turf growing in clayey soil. Once again, this is because of the greater root zone depth of garden bed plants that allows them to access greater amounts of water, thus reducing the need to supply water externally by irrigation.
- Quarterly and annual drainage values are greater for turf than for relatively deeper-rooted garden bed plants.

\textsuperscript{13} As the aim of the analysis was to determine how the soil and landscape parameters impact upon the irrigation water requirement, the rainfall and weather data was kept constant. Weather data corresponding to Kogarah LGA was used for this analysis.
3.6.3 Trees: irrigation water requirement and drainage

Figure 3-9 and Figure 3-10 show the daily irrigation water requirement, drainage and soil–water balance for trees growing in full sun on sandy soil and clayey soil respectively. The daily rainfall and reference ET for the year for which the module was run are plotted in the same graph\(^\text{14}\). The rainfall for the year was 1061 mm; and the annual average reference ET was 1020 mm.

A comparison of daily plots for garden bed plants and trees shows:

- The maximum level of soil–water balance for trees is greater than for garden bed plants. This is because trees have a greater root zone depth compared to garden bed plants (shrubs and groundcovers). The extended root zone results in greater depths of soil becoming available for water storage.
- The greater level of soil–water balance for trees results in a lower frequency of irrigation water requirement, although the amount of water required is greater in order to fill the soil to field capacity, because of the trees’ relatively greater root zone depths.
- The amount of water draining under the root zone of trees is smaller than in the case of turf, again because of the trees’ deeper root zone, which imparts to the soil the capacity to store relatively greater amounts of water.

\(^\text{14}\) As the aim of the analysis was to determine the how the soil and landscape parameters impact upon the irrigation water requirement, the rainfall and weather data was kept constant. Weather data corresponding to Kogarah LGA was used for this analysis.
Figure 3-9: Trees in sandy soil: WASP Module I inputs (daily rainfall and ET) and outputs (irrigation water requirement and drainage)
Figure 3-10: Trees in clayey soil: WASP Module 1 inputs (daily rainfall and ET) and outputs (irrigation water requirement and drainage)

Days 1-365 of Financial Year 1999-2000
Table 3-11: Trees: quarterly and annual irrigation water requirement (mm) and drainage (mm) outputs

<table>
<thead>
<tr>
<th>Tree Parameters</th>
<th>Irrigation water requirement, mm</th>
<th>Drainage under the root zone, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root Zone Depth = 2000mm; $K_L = 0.7$; Maximum Allowable Depletion = 50%</td>
<td>Tree on Sandy soil (PAWC = 0.06mm/mm)</td>
<td>Tree on Clayey soil (PAWC = 0.17mm/mm)</td>
</tr>
<tr>
<td>Q1 (July-Sept)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Q2 (Oct-Dec)</td>
<td>124</td>
<td>0</td>
</tr>
<tr>
<td>Q3 (Jan-Mar)</td>
<td>183</td>
<td>173</td>
</tr>
<tr>
<td>Q4 (Apr-Jun)</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>Annual</td>
<td>367</td>
<td>173</td>
</tr>
</tbody>
</table>

Table 3-11 presents a summary of quarterly and annual irrigation water requirement and drainage values for trees on sandy and clayey soil, as obtained from the daily run of WASP Module 1 for the weather data for 1999/2000\(^{15}\). A comparison of the module outputs between turf and garden bed shows that:

- While irrigation water requirement per irrigation session is relatively greater in case of trees, the total amount applied over a quarter and over the year is less than that applied to turf or garden bed plants. This is true for both sandy soil and clayey soil.
- Trees in clayey soil do not require any irrigation water during Q1, Q2 and Q4, while some irrigation is required during the same quarters for turf growing in clayey soil. Again, this is because of the trees’ greater root zone depth allowing the soil to store more water within the root zone and so reducing the need to supply water externally by irrigation.
- Quarterly and annual drainage values are greater for turf than for relatively deeper-rooted trees. Drainage beneath turf and shrubs can potentially be accessed by the trees’ roots, a natural phenomenon used effectively in agro-forestry for controlling drainage from agricultural crops by growing trees in the crop alleys (Lefroy and Stirzaker 1999). This has implications for

\(^{15}\) As the aim of the analysis was to determine the how the soil and landscape parameters impact upon the irrigation water requirement, the rainfall and weather data was kept constant. Weather data corresponding to Kogarah LGA was used for this analysis.
adjusting (reducing) irrigation water requirements for trees by taking account of the drainage water under turf and shrubs to which the trees have access.

3.7 **Estimating the landscape irrigation budget**

The overall landscape irrigation budget is estimated for each month. It is calculated as the weighted average of the monthly irrigation water requirement of individual landscape components, where the weighting factor is the area of each landscape component relative to the total landscape area. The monthly water requirement of each component is calculated as the monthly sum of the estimated daily irrigation water requirement.

Mathematically, monthly landscape irrigation budget $MLIB_{M1}$, for a given month $M1$, expressed in units of mm, is given by:

$$MLIB_{M1} = \left( \frac{A_{\text{turf}}}{A_{\text{Landscape}}} \right) \times (\Sigma \text{Daily IWR}_{\text{turf}} \text{ for all days of month } M1) + \left( \frac{A_{\text{garden bed}}}{A_{\text{Landscape}}} \right) \times (\Sigma \text{Daily IWR}_{\text{garden bed}} \text{ for all days of month } M1) + \left( \frac{A_{\text{tree}}}{A_{\text{Landscape}}} \right) \times (\Sigma \text{Daily IWR}_{\text{tree}} \text{ for all days of month } M1)$$ (**Equation 3**)

where

- $A_{\text{garden bed}}$ = canopy area of garden-bed, m$^2$
- $A_{\text{Landscape}}$ = area of landscape, m$^2$
- $A_{\text{tree}}$ = canopy area of trees, m$^2$
- $A_{\text{turf}}$ = area of watering zone for turf, m$^2$
- $\text{IWR}_{\text{garden-bed}}$ = irrigation water requirement for garden bed on a day of the given month (estimated by the daily water balance equation), mm
- $\text{IWR}_{\text{tree}}$ = irrigation water requirement for tree on a day of the given month (estimated by the daily water balance equation), mm
- $\text{IWR}_{\text{turf}}$ = irrigation water requirement for turf on a day of the given month (estimated by the daily water balance equation), mm
From Equation 3, it is possible to develop a ready reckoning table of quarterly irrigation budgets for different types of landscapes composed of different proportions of turf and garden bed areas.

An example of such a ready reckoning table is given in Table 3-12 for a moderate water-using (MWU) landscape \( k_v = 0.5 \), under different microclimates, in the suburb of Kogarah on predominantly sandy soil \( \text{PAWC} = 0.06 \text{ mm/mm} \), with MAD fixed at 50%; and similarly for a MWU landscape in Penrith on predominantly clayey soil \( \text{PAWC} = 0.17 \text{ mm/mm} \).

| Table 3-12: Irrigation budgets for MWU landscape in Kogarah and Penrith, with 0%, 50% and 100% turf area |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **MWU** | **KOGARAH** | **PENRITH** | **Full Shade** | **Part Shade** | **Full Sun** | **Full Shade** | **Part Shade** | **Full Sun** | **Full Shade** | **Part Shade** | **Full Sun** | **Full Shade** | **Part Shade** | **Full Sun** | **Full Shade** | **Part Shade** | **Full Sun** | **Full Shade** | **Part Shade** | **Full Sun** | **Full Shade** | **Part Shade** | **Full Sun** | **Full Shade** | **Part Shade** | **Full Sun** |
|        |                |                | 0%  | 50% | 100% | 0%  | 50% | 100% | 0%  | 50% | 100% | 0%  | 50% | 100% | 0%  | 50% | 100% | 0%  | 50% | 100% | 0%  | 50% | 100% | 0%  | 50% | 100% |
| Q1     |                |                | 0   | 43  | 86   | 38  | 65  | 93   | 74  | 97  | 120  | 45  | 94  | 142  | 38  | 65  | 93   | 74  | 97  | 120  | 45  | 94  | 142  | 38  | 65  | 93   |
| Q2     | 45  | 106  | 166  | 96  | 148  | 200  | 155  | 188  | 239  | 45  | 94  | 142  | 38  | 65  | 93   | 74  | 97  | 120  | 45  | 94  | 142  | 38  | 65  | 93   |
| Q3     | 18  | 80  | 141  | 79  | 129  | 180  | 74  | 172  | 211  | 18  | 80  | 141  | 79  | 129  | 180  | 74  | 172  | 211  | 18  | 80  | 141  | 79  | 129  | 180  |
| Q4     | 18  | 80  | 141  | 79  | 129  | 180  | 74  | 172  | 211  | 0   | 0   | 0    | 0   | 0   | 0    | 0   | 0   | 0    | 0   | 0   | 0    | 0   | 0   | 0    |

Chapter 6 describes how landscape irrigation budgets were developed for the domestic garden sites located in the two suburbs using WASP Module 1 and equation 3, and discusses the results of following the process.

### 3.8 Sensitivity analysis of module parameters

WASP Module 1 is a modelling framework which can be used as a foundation to custom-build suburban or regional model to develop irrigation budget and to estimate water saving potential of landscapes within the region, using soil-climate and landscape data specific to the suburb or region. In the absence of field or experimental data on domestic garden vegetation corresponding to different levels of water application which could be used to validate and test the framework, a sensitivity analysis was undertaken to determine the nature of influence each parameter has on
the outputs of the module (even though validation and parameterisation are outside the scope of this thesis).

Model validation ideally involves comparison of model results with independent observations from the system being modelled, but because of insufficient observational data complete validation of WASP Module 1 was not possible. Under such circumstances, sensitivity analysis can be used to help develop a ‘comfort level’ with the model (Frey and Patil 2001). If the model’s response is reasonable from an intuitive or theoretical perspective, then users may have some comfort with the qualitative behaviour of the model even when quantitative precision or accuracy is unavailable.

Sensitivity analysis is also useful for model verification (Frey and Patil 2001), in other words, making sure that the model is doing what it is intended to do. Using sensitivity analysis, the model’s response to changes in one or more inputs can be noted. If the model responds in an unacceptable way to changes in one or more inputs, troubleshooting efforts can be focused on identifying the source of the problem.

Nominal range sensitivity method, also known as local sensitivity analysis or threshold, was used to undertake sensitivity analysis of WASP Module 1. In this method, the effect on model outputs is evaluated by individually varying one of the model inputs across its entire range of plausible values while holding all other inputs at their nominal or base-case values (Cullen and Frey 1999). The difference in output due to change in the input variable is referred to as the sensitivity of the model to that particular input variable (Morgan and Henrion 1990). The sensitivity can be represented as a positive or negative percentage change compared to the nominal solution. Sensitivity analysis can be repeated for any number of individual model inputs.

From the daily soil–water balance equation and development of equation to estimate irrigation water requirement (Section 3.4.1), it is clear that for a given climatic condition (rainfall and reference evapo-transpiration) the estimated irrigation water requirement for an individual landscape component is a function of the following parameters:
• potentially available water-holding capacity (PAWC) of the soil
• effective root zone depth (RZ) of landscape components
• landscape coefficient, $K_L$ (species factor, $k_s$, microclimate factor, $k_{mc}$ and plant density factor, $k_d$)
• maximum allowable depletion level (MAD).

Sensitivity analysis was undertaken for each of the parameters by varying it over a range of possible and practical values while keeping the values of other parameters constant. The rainfall and reference ET data for the same year was used to study all the parameters. The results are plotted in Figure 3-11 to Figure 3-19.

The slope of the xy (line) plot of the module output (irrigation water requirement) against the parameter being varied was an indication of the degree to which the output was sensitive to the parameter being studied. The steeper the slope, the more sensitive is the output to the input parameter value. The input parameters were ranked on the basis of degree of sensitivity.

Sensitivity analysis was useful here in identifying the conditions under which module outputs were more or less sensitive to values of input parameters. Sensitivity plots can also point to the need for further research in obtaining more accurate values for those input parameters to which the module response is relatively more sensitive than others.

3.8.1 Module sensitivity to landscape coefficient $K_L$
Sensitivity of WASP Module 1 to landscape coefficient $K_L$ was studied for sandy soil and clayey soil by fixing the values of all other parameters constant at the following values:

• effective root zone = 500 mm
• maximum allowable depletion level (MAD) = 50%
• soil PAWC = 0.06 for sandy soil; 0.17 for clayey soil.
The landscape coefficient $K_L$ was varied between 0.5 and 1.2, and the quarterly and annual irrigation water requirements were plotted against the range of $K_L$ values.

Figure 3-11 and Figure 3-12 show the results for sensitivity to $K_L$ for sandy soil and clayey soil. They indicate that WASP Module 1 is highly sensitive to the landscape coefficient $K_L$, throughout the range 0.5 to 1.2, in both sandy and clayey soil. This suggests that further research is required to determine the species factor ($k_s$), the microclimate factor ($k_{mc}$) and the plant density factor ($k_d$), which make up the landscape coefficient $K_L$ and how each of these factors influences the ET rate. Such research will help in getting a more realistic estimate of the landscape water requirement.
Figure 3-11: WASP Module 1 response (irrigation water requirement) for variation in $K_L$ values (in sandy soil)
Root Zone Depth = 500mm
Clayey Soil, PAWC = 0.17 mm/mm
Max allowable depletion = 50%

Figure 3-12: WASP Module 1 response (irrigation water requirement) to variation in $K_L$ values (in clayey soil)
3.8.2 Module sensitivity to effective root zone depth

Sensitivity of WASP Module 1 to effective root zone depth (RZ) was studied by holding the other variables constant at the following values:

- MAD = 50%
- landscape coefficient $K_L = 1$
- soil PAWC = 0.06 for sandy soil; 0.17 for clayey soil
Figure 3-13: WASP Module 1 response (irrigation water requirement) to varying root zone depths (in sandy soil)

K(L) = 1
Sandy Soil PAWC = 0.06 mm/mm
Max allowable depletion = 50%
Figure 3-14: WASP Module 1 response (irrigation water requirement) to varying root zone depths (in clayey soil)
The effective root zone depth (RZ) was varied between 150 mm and 3000 mm and the quarterly and annual irrigation water requirement were plotted against the range of RZ values.

From the sensitivity plots (Figure 3-13 and Figure 3-14), it can be concluded that:

- Relative sensitivity of irrigation water requirement to values of root zone depth varies for each quarter, the sensitivity being relatively greater during the spring and summer quarters.
- Irrigation water requirement is more sensitive between RZ values from 150 mm to 300 mm. This implies that when estimating irrigation water requirement for shallow-rooted vegetation components such as turf and grasses, it is important to input root zone depth values that are close to the real values, otherwise there is a risk of grossly underestimating or overestimating the irrigation water requirement.
- Irrigation water requirement shows a relatively greater degree of sensitivity for values greater than 1000 mm. This has implications for deep-rooted vegetation components, such as drought-tolerant shrubs (which are known to have roots deeper than 1000 mm) and trees. It would be worthwhile to research and determine the root zone depths of such species to ensure that any water-saving potential to be achieved through planting them can be estimated accurately.
- Irrigation water requirement is relatively less sensitive for root zone depth values between 300 mm and 1000 mm. Most ground covers and shallow-rooted shrubs fall in this category. This has implications for vegetation in clayey soils and in compacted soils, where the plants are unable to grow deeper roots owing to mechanical resistance from the soil texture.
- In case of plants with deeper root zones (1500-3000mm), the July-Sept irrigation requirement appears to be much higher than the lower root zone depths, which is characteristic of the fact that these plants require infrequent but deep irrigation. However, as can be seen from the plot in Figure 3-14, the annual irrigation requirement of the plants with deeper root zones tend to be lower than that of the plants with shallower root zones.
3.8.3 Module sensitivity to soil PAWC

Sensitivity of WASP Module 1 to potentially available water-holding capacity (PAWC) was studied for vegetation types with shallow, average and deep root depths, holding the values of other parameters constant at the following values:

- effective root zone depth (RZ) = 150 mm (for shallow-rooted plants); 500 mm (for medium-rooted plants); 1500 mm (for deep-rooted plants)
- maximum allowable depletion level (MAD) = 50%
- landscape coefficient, $K_L = 1$, assuming full sun condition.

The potentially available water-holding capacity, PAWC, was varied from 0.05 to 0.20, and the quarterly and annual irrigation water requirement was plotted against the range of PAWC values. This analysis was performed for three different root zone values to determine if the sensitivity was influenced by the effective root zone depth. Figure 3-16, Figure 3-17 and Figure 3-18 show the sensitivity plots for plants with shallow, average and deep root zone depths respectively.

From these results, it can be concluded that:

- Irrigation water requirement is relatively more sensitive to PAWC, for plants with deeper root zone depths.
- For shallow-rooted species (root zone depth 150 mm), a 75% increase in PAWC value resulted in a 7% decrease in the annual irrigation water requirement estimate. In the case of quarterly irrigation water requirement estimates, the change was smaller. Thus irrigation water requirement response is only marginally affected by variation in PAWC value for shallow-rooted species.
- For species with moderate root depths (root zone depth 500 mm), there was a 20% decrease in the annual irrigation water requirement estimate corresponding to a 75% increase in PAWC value.
Determining how the irrigation water requirement response would vary for PAWC values assumed for soils whose broad classification (sandy, loamy sand, sandy loam, loam, clayey loam, clay) is already known by physical examination is of more practical relevance than comparing the sensitivity of irrigation water requirements between two different classes of soil. Noting the relative sensitivity of irrigation water requirement to the range of values that is possible for each class of soil, it can be concluded that:

• For plants with shallow and average root depths, irrigation water requirement is more sensitive towards the sandy end of PAWC (for values in the range 0.05–0.10) than towards the clayey end (for values in the range 0.15–0.20).
• For deep-rooted species (root zone depth 1500 mm), the module response, irrigation water requirement, becomes more sensitive to PAWC towards the clayey end than for PAWC values for sandy soils.
Figure 3-15: WASP Module 1 response (irrigation water requirement) to varying values of water-holding capacity of the soil; for shallow-rooted plants. Assumed root zone depth = 150 mm.
Figure 3-16: WASP Module 1 response (irrigation water requirement) to varying values of water-holding capacity of the soil for plants with moderate root zone depth. Assumed root zone depth = 500 mm.
Figure 3-17: WASP Module 1 response (irrigation water requirement) to varying values of water-holding capacity of the soil for deep-rooted plants. Assumed root zone depth = 1500 mm.
3.8.4  Module sensitivity to maximum allowable depletion (MAD)
Sensitivity of module response (irrigation water requirement) to values of maximum allowable depletion corresponding to different landscape amenity levels was studied for sandy and clayey soils by holding the other variables constant at the following values:

- effective root zone = 500 mm
- landscape coefficient, $K_L = 1$, assuming full sun condition
- soil PAWC = 0.06 for sandy soil; 0.17 for clayey soil.

The maximum allowable depletion level (MAD) was varied between 20% and 90%, and quarterly and annual irrigation water requirements were plotted against the range of MAD values.

From Figure 3-18 and Figure 3-19, it can be concluded that for both clayey and sandy soils, irrigation water requirement is more sensitive for maximum allowable depletion values in the range 50%–70% than in the lower range between 20% and 50%, and the higher range between 70% and 90%.
Figure 3-18: WASP Module 1 response (irrigation water requirement) to varying values of maximum allowable depletion (sandy soil)
Figure 3-19: WASP Module 1 response (irrigation water requirement) to varying values of maximum allowable depletion (clayey soil)
3.9 Chapter summary

WASP Module 1 (Figure 3-20) is a modelling framework based on a rational approach to estimating landscape water requirement for the purpose of water demand management rather than for irrigation scheduling. It incorporates a simple daily water balance equation and takes account of the biophysical factors characteristic of urban landscapes.

![Figure 3-20: Place and function of WASP Module 1 within the overall WASP framework](image)

The assumptions and algorithms used in WASP Module 1 were described. This was followed by running the Module to estimate the irrigation water requirement of turf, shrubs and trees to determine how the estimates respond to the input variables. The estimates of individual landscape components are used later in this thesis in developing the irrigation budget for the overall landscape, such as domestic gardens. This is discussed and demonstrated in Chapter 6.

A sensitivity analysis of the parameters was undertaken. The analysis indicated that the irrigation water requirements of landscape components were most sensitive to landscape coefficient $K_L$ and effective root zone depth $RZ$, and least sensitive to maximum available water-holding capacity of the soil PAWC, and maximum allowable depletion value MAD.
WASP Module 1 can be used for developing irrigation budgets and benchmarks for different types of landscapes. Application of WASP Module 1 to develop such benchmark values is demonstrated in Chapter 6 using site-specific data for two suburbs within the Sydney metropolitan area, each with its own soil–climate and landscape characteristics.

The next chapter provides a description of and discussion of results from the first step in the process of applying the WASP framework, namely characterisation of domestic garden sites in the two suburbs used as case studies for the research.
4. Characterisation of Suburban Domestic Gardens

4.1 Chapter aims

The WASP policy framework proposed in the thesis is centred on the concept of landscape irrigation budget. Chapter 2 introduced and defined the concept of landscape irrigation budget in the context of urban landscapes and management of urban irrigation along with the need for development of a rational approach to estimating a landscape irrigation budget for domestic gardens. A rational method in the form of WASP Module 1 was developed in Chapter 3. The aim of the remaining chapters of the thesis is to demonstrate the application of WASP framework using domestic gardens as case study sites in the two Sydney local government areas of Kogarah and Penrith. The ultimate aims of the application were:

- to characterise the case study domestic gardens located in the suburbs of Kogarah and Penrith LGAs (Chapter 4);
- to develop landscape irrigation budgets for those gardens (Chapter 5); and
- to estimate the water saving potential (before and after water restrictions) for those gardens (Chapter 6).

The aim of this chapter is to describe the survey process which was undertaken to characterise the domestic gardens and discuss its results. The aim of the survey was to understand those characteristics of domestic gardens which have a direct influence on their irrigation water requirements.

A review of the literature showed that researchers have studied and characterised domestic gardens with different objectives. Jacob (1992), Henderson et al. (1998) and Jurkow (2000) studied private gardens in North American suburbs with the view to determine the personal motivations and the social and physical patterns behind the emergence of garden form. As part of a larger survey of biodiversity in gardens in Sheffield, UK, Thompson et al. (2003, 2004) studied the composition and diversity of the flora in 60 gardens along with lawn flora in 52 gardens and compared them with floristic data from semi-natural habitats in central England and derelict urban land in Birmingham, UK, with the view of understanding the habitat characteristics of the
lawn and garden bed flora. In the only study of its type, Zagorski et al. (2004) related floristic garden types in two contrasting suburbs of Hobart, Tasmania, Australia to the attitudes of their gardeners. Daniels and Kirkpatrick (2006) studied 214 back or front gardens in ten suburbs of Hobart to understand the relative influence of garden characteristics such as vegetation structure and floral characteristics on the abundance and richness of bird species in the suburbs. Kirkpatrick et al. (2007) studied the domestic gardens in Hobart to determine the relationships between the dependent variables, presence of trees in a front garden and front garden type, and socio-economic, environmental and demographic variables, at the suburb scale in Hobart. Perry and Nawaz (2008) studied aerial photos of domestic gardens in a 1.16 square kilometre suburban area of Leeds in northern England, with the view to mapping the changes in the impervious cover from 1971 to 2004.

No study, however, aimed at determining those characteristics of domestic gardens that have a direct influence on the irrigation or watering requirement or demand of the domestic garden. These factors include:

- area characteristics, such as landscape area and proportion of area that is dedicated to turf
- water use characteristics of shrubs and groundcover planted in the garden
- microclimate characteristics.

These characteristics gain even more importance in the context of analysing urban irrigation demand at a regional or suburban scale. Understanding these characteristics of a sample of domestic gardens in a suburb can provide the data necessary to estimate the urban irrigation demand and water-saving potential that exists at suburban scale. To determine these specific characteristics, the thesis developed a methodology of landscape characterisation survey that can be practically implemented as a first step in applying the WASP framework to analyse the irrigation demand of domestic gardens in a given soil–climate zone.

The landscape characterisation survey involved studying the geo-coded aerial photographs of 222 single detached dwellings (SDDs) spread across nine different
suburbs in the Kogarah LGA and 192 SDDs spread across seven suburbs in the Penrith LGA. In addition, 19 out of the 222 domestic gardens in Kogarah and 23 out of the 192 domestic gardens in Penrith were visited and physically inspected to identify the plantings constituting the garden.

The results for each of the two LGAs are presented to demonstrate the relevance of the following characteristics of domestic gardens to the ultimate aim of determining their aggregate water saving potential:

- area characteristics
- water use characteristics
- microclimate characteristics

4.2 Area characteristics

Analysing area characteristics involved using the geographic information system (GIS) software MapInfo to perform desktop analysis of the geo-coded aerial photographs of the selected gardens. The aim of the analysis was to obtain and estimate for the individual gardens making up the selection their landscape area and its distribution between turf and non-turf areas.

A total of sixteen patches of geo-coded aerial photographs of single detached houses from the Kogarah LGA and seventeen patches of geo-coded photos of houses located in the Penrith LGA were used to determine the landscape characteristics of the domestic gardens. Each patch of aerial photos included between 6 and 16 houses; the garden of at least one house in each patch was inspected. The other gardens were in close proximity to the garden that was visited.

As the photographs were geo-coded, they were analysed using MapInfo. Once geo-coded, they were presented completely in alignment with the geographical coordinates. Thus the mapped streets and house boundaries were viewed and mapped on top of the aerial photos. The MapInfo software has the facility to tabulate and manipulate any mappable data. It also has a feature whereby polygons can be drawn
on a map and their areas calculated and tabulated. Using this feature, the polygons were drawn to mark the turfed areas and garden bed areas of the domestic gardens being studied, their areas then calculated and tabulated along with the property address corresponding to the garden.

Figure 4-1 shows an example of a patch of aerial photos from Penrith LGA, with polygons drawn to mark the turf area (green) and garden bed area (blue) in each property (which was identified with a property identification number). The property whose identification number (39) appears in yellow was the property that was inspected and its garden plants identified.

The areas of turf and garden bed of each garden site included in the patch of aerial photos were estimated and tabulated. The landscape area was calculated as sum of the turf area and garden bed area. The percentage of the area that constituted turf was also calculated. Because the landscape area and the proportion made up of turf varied widely between houses, the range of variation in both was estimated. The average and median values for both variables (landscape area and turf area expressed as percentage of landscape area) were calculated. A comparison of median and average values is helpful in alerting the researcher to significantly skewed samples; however, for the sample of photographs that were studied, both in Kogarah and Penrith LGAs, the median and average did not differ significantly, suggesting that the sample selected formed a symmetrical bell-shaped normal distribution.
Figure 4-1: A patch of geo-coded photographs of eighteen houses in Penrith showing the polygons that were drawn to mark the turf area and garden bed area in the gardens of the properties to calculate their area using the GIS software MapInfo®.

4.2.1 Results

**Kogarah**

The results from calculating the area of turf and garden bed for the 222 domestic gardens in the Kogarah LGA are tabulated in Table 4-1. Suburb-by-suburb analyses of the landscape characteristics, based on the results shown in Table 4-1, are plotted in Figure 4-2 and Figure 4-3. This suburb-by-suburb analysis reveals the differences that exist in the landscape characteristics of domestic gardens between the suburbs within Kogarah LGA. The following observations are noteworthy:

- The average landscape area was smaller in suburbs that were located closer to the bay, such as Kogarah Bay, Kyle Bay and Sans Souci.
- The proportion of area that is devoted to turf varied from zero to 100%, the median value ranging from about 50% in Carss Park and Kyle Bay to as high as 93% in Oatley.
### Kogarah Landscape Characterization Summary

<table>
<thead>
<tr>
<th>Patch ID</th>
<th>Suburb</th>
<th>No of sites</th>
<th>Landscape Area, sq m</th>
<th>% Turf Area</th>
<th>Water Use Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Range</td>
<td>Median</td>
<td>Average</td>
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<td>59-319</td>
<td>205</td>
<td>194</td>
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<td>133-450</td>
<td>201</td>
<td>231</td>
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<tr>
<td>Kog_21</td>
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<td>64-339</td>
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<td>135</td>
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<tr>
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<td>CARLTON</td>
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<td>73-261</td>
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<td>7</td>
<td>60-167</td>
<td>142</td>
<td>118</td>
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<tr>
<td>Kog_12</td>
<td>HURSTVILLE GROVE</td>
<td>21</td>
<td>18-288</td>
<td>162</td>
<td>167</td>
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<td>19-271</td>
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<td>14</td>
<td>31-213</td>
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</table>
Figure 4-2: Kogarah: Average landscape area of domestic gardens by suburb

Figure 4-3: Kogarah: Suburb-by-suburb analysis of turf area in home landscape
Penrith

The results from studying the seventeen patches of geo-coded aerial photographs, together amounting to 192 properties, are presented in Table 4-2. Suburb-by-suburb analyses of the landscape characteristics, based on the results shown in Table 4-2, are plotted in Figure 4-4 and Figure 4-5.

The suburb-by-suburb analysis reveals the differences that exist in the landscape characteristics of domestic gardens between suburbs in the Penrith LGA. The following observations are noteworthy in the context of developing any policies and programs for outdoor water savings:

- The landscape area of domestic gardens varied widely within each suburb. The maximum area is 8–10 times the minimum (e.g. from 14 to 185 square metres in Kingswood, 61 to 663 square metres in South Penrith). However, the median landscape area between suburbs is in the range of 121–251 square metres, and did not vary as widely.
- The median landscape area was smaller in case of Glenmore Park, Kingswood and Cambridge Gardens.
- The proportion of the area devoted to turf varies from zero to 100%, the median value ranging from about 65% in Emu Plains to as high as 93% in Cambridge Gardens.
Table 4-2: Penrith: Area and water-use characteristics of domestic gardens

<table>
<thead>
<tr>
<th>Patch_ID</th>
<th>SUBURB</th>
<th>No of Sites</th>
<th>Landscape Area</th>
<th>% Turf</th>
<th>Water Use Characteristics</th>
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</thead>
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<td>Pen_01</td>
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<td>43-220</td>
<td>150 140</td>
<td>34-100 89% 84% LWU</td>
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<td>Pen_02</td>
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<td>86-395</td>
<td>251 236</td>
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<tr>
<td>Pen_03</td>
<td>Cambridge Park</td>
<td>18</td>
<td>49-274</td>
<td>143 149</td>
<td>42-100 82% 80% MWU</td>
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<tr>
<td>Pen_04</td>
<td>Cranebrook</td>
<td>10</td>
<td>63-270</td>
<td>141 141</td>
<td>28-94 75% 74% LWU</td>
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<tr>
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<td>Cranebrook</td>
<td>17</td>
<td>108-319</td>
<td>214 212</td>
<td>30-100 71% 70% LWU</td>
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<tr>
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<td>Emu Plains</td>
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<td>69-421</td>
<td>152 174</td>
<td>18-100 58% 65% HWU</td>
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<td>Emu Plains</td>
<td>14</td>
<td>82-262</td>
<td>170 161</td>
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<td>Glenmore Park</td>
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<td>98-265</td>
<td>153 175</td>
<td>27-100 76% 71% LWU</td>
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<td>Pen_10</td>
<td>Glenmore Park</td>
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<tr>
<td>Pen_11</td>
<td>Kingswood</td>
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<td>177 188</td>
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<tr>
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<td>Kingswood</td>
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<td>55-234</td>
<td>153 142</td>
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<td>121 108</td>
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<td>Pen_16</td>
<td>South Penrith</td>
<td>11</td>
<td>30-376</td>
<td>162 157</td>
<td>66-100 91% 87% LWU</td>
</tr>
<tr>
<td>Pen_17</td>
<td>South Penrith</td>
<td>9</td>
<td>61-663</td>
<td>183 214</td>
<td>75-100 84% 87% LWU</td>
</tr>
</tbody>
</table>
Figure 4-4: Penrith: Home landscape area suburb-by-suburb

Figure 4-5: Penrith: Suburb-by-suburb analysis of turf area in home landscapes
4.2.2 Area characteristics: Kogarah vs. Penrith

Figure 4-6, Figure 4-7 and Figure 4-8 display respectively the percentage distribution of overall landscape area, turf area and garden bed area of surveyed garden sites in Kogarah and Penrith LGAs.

Figure 4-6: Kogarah vs. Penrith: Percentage distribution of landscape area of home gardens

Figure 4-7: Kogarah vs. Penrith: Percentage distribution of area of turf in home gardens
4.2.3 Relevance of area characteristics

In management of the aggregate water demand for domestic gardens, the area is an obvious and important variable because the estimation of aggregate volume of water that can potentially be saved in the gardens of a particular suburb within a local government area would be proportional to the average landscape size and the average size of turf and garden bed areas. Also, depending on the correlation that may be found between the landscape area or turf area or garden bed area and its water saving potential, information on the area’s characteristics can provide useful clues as to which landscapes should be targeted in outdoor water-saving programs to get the maximum saving.

4.3 Water-use characteristics

4.3.1 Method

The selection and recruitment of domestic gardens for physical observation were described in Chapter 2. Water use characteristics of the gardens were determined by noting:

- names, number and type (tree, shrub or ground cover) of plants that made up the garden composition; and

- water-use characteristics of those plants.

During the garden visits, the shrubs, ground covers and trees were identified and their common names and scientific (species) names noted and recorded, with assistance from a horticulturist who accompanied the researcher.
The names of the plantings found in the domestic gardens were tabulated under the category of trees, shrubs and ground cover. A colour-coding system was used to facilitate counting of plantings belonging to each of the three categories of water use. Three different shades of blue were used for shading the cells containing the plant names. The darkest shade denoted high water using plants, medium blue moderate water using plants, and light blue low water using plants. Once colour coded, the numbers of species in each of the categories were counted to determine the overall water use characteristics of the garden. The water use characteristics of the maximum number of plants was determined to be the water use characteristic of the garden. This method is contrary to the traditional approach that sets the water requirement based on the highest water using plant. In either approach, one or the other plant category is bound to be compromised on quality due to overwatering (in case of conventional approach) or due to under-watering (in the method adopted in the research). Hence, the latter approach was considered appropriate for this research because it was in keeping with the objective of water conservation, to ensure the maximum number of plants in urban landscapes are maintained with minimum volume of water. Table 4-3 gives an example of the colour-coding system.

Table 4-3: An example of the colour coding system used for the water use characteristic analysis of a domestic garden

<table>
<thead>
<tr>
<th>Shrub: Botanical Name</th>
<th>Shrub: Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camellia</td>
<td>Camellia</td>
</tr>
<tr>
<td><em>Strelitzia reginae</em></td>
<td>Bird of Paradise</td>
</tr>
<tr>
<td>Azalea</td>
<td>Azalea</td>
</tr>
<tr>
<td>Clivia</td>
<td>Clivia</td>
</tr>
<tr>
<td>Gardenia</td>
<td>Gardenia</td>
</tr>
<tr>
<td>Grevillea</td>
<td>Grevillia</td>
</tr>
</tbody>
</table>

LEGEND
- High Water User (HWU)
- Moderate Water User (MWU)
- Low Water User (LWU)

Note: The plant count for domestic garden site # 6 is HWU = 4 Shrub+0 Ground cover; MWU = 4 Shrub+1 Ground cover; LWU = 5 Shrub+2 Ground cover. Thus, as LWU has the maximum number of plants, the water use characteristics of site # 6 was assigned as LWU.
4.3.2 Results

The water-use characteristic determined for the garden site inspected was assumed to apply to the gardens in close proximity. Once the water use characteristics were determined for all the domestic gardens included in the patches of aerial photographs, a suburb-by-suburb analysis was performed to determine the predominant water use characteristic of the gardens in each suburb. The results of these analyses are presented in Figure 4-9 (Penrith) and Figure 4-10 (Kogarah).

The water use characteristics of all the plants found in the gardens visited were also analysed to get a collective picture of the predominant and popular garden plantings in each of the LGAs.

Table 4-4 and Table 4-5 respectively list the shrub species and ground cover species that were found to be popular (identified in at least 1 in 5 garden sites, equivalent to 20% frequency) in the 38 garden sites surveyed in the Kogarah LGA.

Table 4-6 and Table 4-7 respectively list the shrub species and ground cover species that are popular (identified in at least 1 in 5 garden sites, equivalent to 20% frequency) in the 46 garden sites surveyed in the Penrith LGA.
Table 4-4: Popular shrub species in domestic gardens of Kogarah LGA

<table>
<thead>
<tr>
<th>Shrub: Botanical Name</th>
<th>Shrub: Common Name</th>
<th>% of Total Shrubs (N = Number of Shrub Species Identified = 422)</th>
<th>Frequency of Count (N = Number of Garden Sites = 38)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camellia</td>
<td>Camellia</td>
<td>5%</td>
<td>58%</td>
</tr>
<tr>
<td>Strelitzea reginae</td>
<td>Bird of Paradise</td>
<td>4%</td>
<td>42%</td>
</tr>
<tr>
<td>Azalea</td>
<td>Azalea</td>
<td>3%</td>
<td>37%</td>
</tr>
<tr>
<td>Clivia</td>
<td>Clivia</td>
<td>3%</td>
<td>34%</td>
</tr>
<tr>
<td>Gardenia</td>
<td>Gardenia</td>
<td>3%</td>
<td>32%</td>
</tr>
<tr>
<td>Grevillea</td>
<td>Grevillia</td>
<td>3%</td>
<td>29%</td>
</tr>
<tr>
<td>Murraya paniculata</td>
<td>Orange Jasmine</td>
<td>3%</td>
<td>29%</td>
</tr>
<tr>
<td>Rosa</td>
<td>Rose</td>
<td>3%</td>
<td>29%</td>
</tr>
<tr>
<td>Nandina</td>
<td>Sacred Bamboo</td>
<td>2%</td>
<td>26%</td>
</tr>
<tr>
<td>Agapanthus africanus</td>
<td>Agapanthus</td>
<td>2%</td>
<td>24%</td>
</tr>
<tr>
<td>Nephrolepis cordifolia</td>
<td>Fishbone Fern</td>
<td>2%</td>
<td>24%</td>
</tr>
<tr>
<td>Geranium oreganum</td>
<td>Geranium</td>
<td>2%</td>
<td>24%</td>
</tr>
<tr>
<td>Crassula argentea</td>
<td>Jade</td>
<td>2%</td>
<td>24%</td>
</tr>
<tr>
<td>Trachelospermum jasminoides</td>
<td>Star Jasmine</td>
<td>2%</td>
<td>21%</td>
</tr>
<tr>
<td>Macrozamia Communis</td>
<td>Burrawang</td>
<td>2%</td>
<td>18%</td>
</tr>
</tbody>
</table>

Table 4-5: Popular groundcover species in domestic gardens of Kogarah LGA

<table>
<thead>
<tr>
<th>Groundcover (GC): Botanical Name</th>
<th>Groundcover: Common Name</th>
<th>% of Total GCs (N = Number of GC Species Identified = 60)</th>
<th>Frequency of count (N = Number of Garden Sites = 38)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiopogon japonicus</td>
<td>Mondo Grass</td>
<td>17%</td>
<td>26%</td>
</tr>
<tr>
<td>Sedum</td>
<td>Sedum</td>
<td>10%</td>
<td>16%</td>
</tr>
<tr>
<td>Convolvulus mauritanicus</td>
<td>Ground morning glory</td>
<td>7%</td>
<td>11%</td>
</tr>
<tr>
<td>Osteospermum ecklonis</td>
<td>Seaside Daisy</td>
<td>7%</td>
<td>11%</td>
</tr>
<tr>
<td>Hymenocallis littoralis</td>
<td>Spider Lily</td>
<td>7%</td>
<td>11%</td>
</tr>
<tr>
<td>Geranium</td>
<td>Geranium</td>
<td>5%</td>
<td>8%</td>
</tr>
<tr>
<td>Gazania</td>
<td>Gazania</td>
<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td>Convolvulus cneorum</td>
<td>Silver bush</td>
<td>3%</td>
<td>5%</td>
</tr>
</tbody>
</table>
The plantings were further analysed to determine the percentage breakdown of the low, moderate and high water using plantings that were popular and predominant. The results of these analyses are presented in Figure 4-9 and Figure 4-10.
Figure 4-9: Penrith: Percentage break-up of popular plant species by water use characteristic

Figure 4-10: Kogarah: Percentage break-up of popular plant species by water-use characteristic
4.3.3 Relevance of water-use characteristics

Prior to determining the water saving potential of domestic gardens in a suburb, each garden is assigned a landscape irrigation budget, which is based on the water using characteristic of a typical garden in the suburb. For planning purpose, while it is not feasible to determine the water-use characteristic of every individual domestic garden site, it is possible to determine the water-use characteristic of strategically sampled sites and estimate water-saving potential on the basis of the prevalence of those characteristics found in the strategically sampled sites.

Once the framework is set up to utilise information on the water-use characteristics of domestic gardens, there is potential to later improve the quality of data by inviting home owners to supply information on the plants in their garden. The opportunity also exists to make use of data that may have been collected from previous programs such as landscape assessment programs.

Therefore, determining the water-use characteristic of the domestic garden has a strategic significance.

4.4 Microclimate characteristics

4.4.1 Method

Identifying microclimate characteristics involved selecting domestic garden sites from the existing and established gardens located in the Kogarah and Penrith LGAs. Gardens from both areas were randomly selected to obtain a sample that included gardens:

- from different sub-zones in each area;
- of different shapes and sizes;
- with different aspects (in relation to orientation to the north) to ensure representation of various microclimates.

Microclimate is here defined as the climatic conditions, particularly temperature and exposure to wind, that prevail locally within a garden or a section of a garden. As discussed in Chapters 2 and 3, the microclimate influences the evapo-transpiration rate and therefore the plant and landscape water requirement. Microclimate is influenced by:
• the orientation of the landscape with reference to the north–south axis (Ambrose 2008);
• the presence of an impervious structure in close proximity to a garden zone (turf or garden bed) that can radiate heat, potentially increasing the temperature of the zone, thereby raising the rate of evapo-transpiration and the water requirement;
• the presence of shade in close proximity to a garden zone that can potentially reduce temperature, thereby decreasing the rate of evapo-transpiration and the water requirement.

The domestic gardens surveyed for this research were typically made of a back yard and front yard with the built-up house area between the two. Consequently, with respect to orientation, the yards attached to a property that lies along an east–west axis were exposed to full sun for most of the day, compared to the yards attached to a house lying along a north–south axis (Figure 4-11).

For simplicity, the orientation of the yards attached to the single detached dwellings was used as the main criterion in determining the microclimate characteristic of the garden. The following rule was used to assign the microclimate characteristic to individual garden forming the selection of domestic gardens. It is adapted from the rule used by developers and architects in determining solar access based on lot orientation (Ambrose 2008):

• High microclimate, implying exposure to full and direct sun for most part of the day, for landscapes that lay along and within ± 10 degrees of the east–west axis.
• Low microclimate, implying not being exposed to full sun or being exposed to shade for most part of the day, for landscapes that lay along and within ± 10 degrees of the north–south axis.
• Moderate microclimate, implying exposure to part sun and part shade for most of the day, for landscapes that lay anywhere between ± 10 degrees of the north–south axis and ± 10 degrees of the east–west axis.
Figure 4-11: Microclimate factor of the garden based on orientation of the house, with respect to north-south (N–S) axis: E = east; W = west; N–S facing = full shade; E–W facing = full sun; NW–SE or NE–SW facing = part sun part shade, assuming that the front yard and back yard are located along the shorter walls of the house.

When the presence of a significantly large impervious area exposed to full sun or shade was noted, the microclimatic factor value was adjusted to modify the microclimate characteristic determined on the basis of orientation. Chapter 2 contains the details of the microclimate characteristics of the domestic gardens surveyed in the Kogarah and Penrith LGAs.

Figure 4-12 is an example of how the combination of house orientation and presence of shading and/or heat radiating impervious surface were used to assign the microclimate factors to the domestic gardens. Note that the domestic garden sites identified as 370, 363, 364, 365 and 366 lie along the east–west axis, and have therefore been assigned H factor; the garden sites with IDs 382 and 383 lie along the north–south axis, and hence are assigned an L factor; the garden site ID 388 is oriented along the NE–SW axis and therefore has been assigned M factor. These ratings are listed in Table 4-8.
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Figure 4-12: An example of assigning microclimate factors to domestic garden sites

Table 4-8: Example of microclimate factors assigned to domestic garden sites

<table>
<thead>
<tr>
<th>Property ID</th>
<th>370</th>
<th>388</th>
<th>363</th>
<th>364</th>
<th>365</th>
<th>366</th>
<th>382</th>
<th>383</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microclimate</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>L</td>
</tr>
</tbody>
</table>

4.4.2 Results
The microclimatic characteristic of domestic gardens in the form of microclimate factor $k_{mc}$ was determined for every domestic garden included in the aerial photos. An example of the microclimatic characteristic noted for every garden in one of the patches of aerial photographs in Kogarah LGA is given above.

4.4.3 Relevance of microclimate characteristic
The microclimate characteristic served as an input into the biophysical module which determined the irrigation budget for the domestic garden. As the domestic garden irrigation budget was determined on the water use characteristic and the microclimate factor, these are important parameters for achieving the next objective of estimating the landscape irrigation
budget. It is feasible to determine the microclimate characteristic of individual gardens using aerial photographs, unlike the water use characteristic, which must be estimated. The $k_{mc}$ factor was determined for every individual garden.

The next chapter discusses the development of the landscape irrigation budget for the domestic gardens in Kogarah and Penrith using the WASP Module 1. The landscape characterisation results are used as inputs to biophysical model of WASP Module 1. They are, therefore, a necessary element within the WASP framework.

### 4.5 Chapter Summary

Landscape characterization is an important first step in building a picture of the urban irrigation demand and its water saving potential at a suburban or regional level using the WASP framework. The objective of landscape characterization is to determine values for those parameters of landscapes, which have a direct influence on total irrigation water requirement of the landscape. Hence, a systematic method to determine the area characteristics, plant water use characteristics and micro-climate characteristics of the landscapes in a suburb was described.

The method involves making physical visits to a sample of the landscape sites in the suburb and analysing the geo-coded aerial photographs of the landscape sites. Using the method, the domestic gardens in the suburbs of Kogarah and Penrith LGAs were characterized.

Understanding the landscape characteristics is important as they will inform the areas that would need to be targeted by policies and programs that would be developed to realize the water saving potential quantified and mapped using the WASP framework.
5. Developing Landscape Irrigation Budgets for Domestic Gardens

5.1 Introduction and chapter aims

Outdoor demand management programs present a unique challenge to agencies that have the responsibility of managing urban water demand. One of the primary reasons for this is that it is difficult to quantify the water-saving potential of urban irrigation demand, which contributes from 90% to 100% of the outdoor demand.

Water saving potential, in the demand management context, is defined as the difference between the water demand ‘that is’ (existing demand) and ‘that could be’ (aspired optimum demand). While the absence of dedicated meters to monitor water used for irrigation of gardens hinders the estimation of water demand ‘that is’, the lack of a scientific tool that can estimate landscape irrigation budgets for given soil, climate and landscape characteristics prevents the estimation of water demand (by landscapes) ‘that could be’. This chapter explores the concept of a landscape irrigation budget that has the potential to enable the quantification of the water saving potential of existing established landscapes within an urban region.

It is important to note that ‘landscape irrigation budget’ is a theoretical value that guides the aspiration of managing urban irrigation demand. It depends upon the landscape outcome that is aspired to (desired), with a view to achieving sustainability with respect to urban green spaces as well as the water resources needed to maintain them. Hence, choosing the type(s) of (desired) landscape and landscape outcomes, with respect to water-use characteristics and amenity level, is an important part of developing the irrigation budget.
Focus of this chapter is WASP Module 1 (Figure 5-1) and has two aims. The first is to compare the rational approach to estimating landscape irrigation budget, as used in WASP Module 1, with two empirical methods that are conventionally used for developing irrigation budgets by managers of turf areas and public open space. Irrigation budgets are calculated for turf and garden beds located in Kogarah and Penrith, using WASP Module 1 and the two empirical methods, and the resulting budgets are compared by method. The methods have been compared in order to test one of the premises of the policy framework proposed in the thesis, that:

\[ a \text{ landscape irrigation budget estimated using a rational method is necessary for facilitating management of urban irrigation demand.} \]

The second aim is to estimate landscape irrigation budgets using WASP Module 1, for domestic gardens in Kogarah and Penrith. A comparison of landscape irrigation budgets for the two suburban areas, representing two different soil–climate zones, is undertaken to explore the premise that:

\[ a \text{ rational method for estimating landscape irrigation budget, such as WASP Module 1, has the capacity to develop budgets that are commensurate with variations in soil and climate characteristics.} \]
The chapter begins with a description of the various steps involved in the process of developing irrigation budgets for landscapes, which is followed by a discussion of the input parameters used to apply the process to the suburbs of Kogarah and Penrith, and a description of the nine landscape scenarios for which the irrigation budgets are developed.

The chapter concludes with a presentation and discussion of the following results:
1. Comparing the landscape irrigation budgets estimated for the nine different landscape scenarios using empirical methods with those estimated using WASP Module 1.
2. Comparing landscape irrigation budgets estimated using WASP Module 1 for the domestic gardens located in Kogarah and Penrith.

5.2 Method of estimating landscape irrigation budget

This section describes the various steps involved in the process of applying WASP Module 1 to develop irrigation budgets for the landscapes in the two study areas. Figure 5-2 gives a schematic representation of the three main steps involved:

1. Performing a *100-year daily run of WASP Module 1* using input parameters that represent the soil, climate and landscape characteristics of the suburb and landscape type for which the irrigation budget is to be developed. A daily run of the module will produce, as output, the daily irrigation water requirement of individual landscape components corresponding to 100 years of daily climate data.

Use of long-term data such as figures for 100 years imparts a greater level of confidence to the budget that is developed by the Module. In practical terms, a median monthly value obtained from a run using 100-year daily data implies that the irrigation water requirement estimated by the Module has a 50% probability of being adequate for a landscape.
The input parameters required include:

**Plant parameters:**
Root depth corresponding to each landscape component, that is, turf, garden bed plants and trees, is the input plant parameter. The landscape components are selected relevant to the landscape type for which the irrigation budget is to be developed. For example, the landscape components of:

- a sports ground would be turf
- a domestic garden would be turf, garden bed plants and trees
- a specific ornamental landscape could be turf, shrubs and ground cover.

Values for root depths are assumed.

**Soil parameters:**
Available water-holding capacity of the soil type(s) predominant in the suburb is the input soil parameter required by the Module. This can be obtained either by:

- doing a physical examination to classify the soil and using the published literature values corresponding to the soil classification; or
- performing a physical test on the predominant types of soil that are found in the region and soil types that are commonly used in the landscape site.

The former method was used in developing irrigation budgets for this case study.

**Landscape parameters:**
The published values for the following parameters are input to the Module:
• Species factors corresponding to the aspired water-use characteristics of the landscapes in the suburb.
• Microclimate factors corresponding to the microclimate characteristics of the landscapes in the suburb.
• Maximum allowable depletion (MAD) values corresponding to the aspired amenity levels of the landscape.

2. Using a spreadsheet (MS Excel®) based tool called the 100-Year Data Sorter that was developed for the thesis with the specific objective of sorting the output from the 100-year daily run of WASP Module 1 to obtain median monthly irrigation budgets for each of the landscape components.

3. Using a spreadsheet (MS Excel®) based tool called the Landscape Irrigation Budget Estimator that was developed for the thesis with the specific objective to estimate the irrigation budget for different landscape types created by a combination of water use characteristics, microclimate and amenity level.
Figure 5-2: Three data analysis stages contained in WASP Module 1
5.3 Input parameters

Prior to describing and discussing the results for monthly and quarterly irrigation budgets, the input parameters specific to calculations for the Kogarah and Penrith areas are outlined and discussed in this section.

5.3.1 Weather parameters

The weather data, namely rainfall and reference ET\textsuperscript{16}, were compiled for the financial year rather than calendar year. This ensured that the irrigation budgets developed matched the quarters for which the metered water consumption data of residential customers were recorded and billed.

Rainfall and Reference evapo-transpiration (ET\textsubscript{o}) data were obtained from Data Drill, a website of the Queensland Department of Natural Resources (http://www.bom.gov.au/silo). Data Drill provides spatially interpolated data from daily rainfall records provided by the Australian Bureau of Meteorology from its network of recording stations. The geographic location coordinates corresponding to Kogarah and Penrith were provided to SILO, specifying the period for which the climatic data were required for the research. From the data obtained for the years 1906–2006, it was possible to construct annual rainfall for financial years. The 100-year period began with 1 July 1906–30 June 1907 and ended with 1 July 2005–30 June 2006.

As can be seen from the 100-year annual rainfall plots shown in Figure 5-3 and Figure 5-4, annual rainfall in the Kogarah area is consistently about 25% higher than in Penrith. However, as can be seen from the 100-year annual reference ET data plotted in Figure 5-5 and Figure 5-6, the ET\textsubscript{o} values for Kogarah and Penrith are very similar. Penrith has a marginally greater value of annual ET\textsubscript{o} than the annual ET\textsubscript{o} for Kogarah.

\textsuperscript{16}Reference ET as estimated by the FAO56 Method (FAO 1998), known as FAO56 ET or ET\textsubscript{o}, was used.
Figure 5-3: 100 years of annual rainfall data plotted for Kogarah and Penrith

Figure 5-4: Percentile graph of 100-year rainfall data for Kogarah and Penrith
Figure 5-5: 100 years of annual reference ET data plotted for Kogarah and Penrith

Figure 5-6: Percentile graph of 100-year reference ET data for Kogarah and Penrith
5.3.2 Soil and landscape input parameters

In addition to weather parameters, the soil characteristics predominant on the garden sites, available water-holding capacity (PAWC) in particular, are required as input to WASP Module 1.

Assumptions regarding plant and landscape parameters need to be explicitly defined and input into the Module. These include the parameters:

- root zone depth, RZ, of various plant types in the garden
- water use factor, $k_s$, for each plant type
- microclimate factor, $k_{mc}$
- maximum allowable depletion, MAD (to match the required amenity level).

The values used for developing the landscape irrigation budgets for Kogarah and Penrith are shown in Table 5-1.

<table>
<thead>
<tr>
<th>Parameter type</th>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Daily data for Kogarah and Penrith</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>PAWC</td>
<td>mm/mm</td>
<td>Values published in soil science literature (Handreck &amp; Black 1994)</td>
</tr>
<tr>
<td></td>
<td>Kogarah</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Penrith</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Plant</td>
<td>Root zone depth, RZ</td>
<td>mm</td>
<td>Values assumed, based on root zone depths published for landscape vegetation (Anonymous 2006)</td>
</tr>
<tr>
<td></td>
<td>Turf</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Garden bed</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tree</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>Landscape</td>
<td>Water use factor, $k_s$</td>
<td>Turf/garden bed/tree</td>
<td>Table 5-3, Table 5-4</td>
</tr>
<tr>
<td></td>
<td>Microclimate factor, $k_{mc}$</td>
<td>Turf/garden bed/tree</td>
<td>Table 5-3, Table 5-4</td>
</tr>
<tr>
<td></td>
<td>Amenity factor, MAD</td>
<td>Strong moderate</td>
<td>50%</td>
</tr>
</tbody>
</table>
5.4 Potential landscape scenarios

Developing different scenarios of landscapes that can potentially exist or be aspired to is an important part of the process. Potential landscape scenarios for both areas were developed based on:

- the water-use characteristics and amenity levels of landscapes aspired to in order to achieve the goal of water saving
- microclimate characteristics.
Table 5-2

As shown in Table 5-2, nine landscape scenarios were identified for which landscape irrigation budgets would be developed. The following points are noteworthy in their development:

- For simplifying the estimation of landscape irrigation budget of domestic garden, the landscape was considered to be made up of only two predominant components namely, turf and garden bed made of shrubs
  - Tree was ignored for the purpose of this analysis. This was a reasonable simplification based on the fact that as noted in Chapter 3 irrigation requirement of deep rooted plantings such as trees is often negligible over a month. And even when the irrigation depth required is high for at least one month in a year, when multiplied by the canopy area, the overall volume required by the tree is relatively less than the volume of irrigation required by the turf and shrubs. And the fact that trees owing to their deep roots have access to the water drained from under the shrubs and turf also makes this assumption a reasonable one.
  - Groundcover was not separately accounted for as turf area whose root depth is similar to groundcover was assumed to account for groundcover.
  - This simplification was also consistent when water consumption of domestic gardens were being studied through the use of their aerial photographs. This is because aerial photographs allow for visual classification of domestic garden into two distinct areas – turf and garden bed.

- Low and moderate water use landscapes were included, as they represent scenarios that have the potential to provide water savings through water-efficient landscape design.

- Irrigation budgets were developed for high water use landscapes to help determine the water saving potential that can be achieved through improvements in the design of irrigation systems.

- Three microclimate characteristics were included in developing the landscape type because houses (and yards) in both areas are oriented in directions that
contribute to three different microclimate conditions. In addition to the orientation aspect, other site-specific conditions may contribute to modifying the microclimate.

- Plant density was assumed to be average resulting in a $k_d$ value equal to 1.
- The amenity level was assumed to be moderate for all landscapes in order to limit the number of landscape types. Moderate amenity level corresponds to a MAD value of 50%. This applied to all the nine landscape types.
Table 5-2: The nine landscape scenarios

<table>
<thead>
<tr>
<th>Microclimate characteristic</th>
<th>Water-use characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full shade</td>
<td>Low, LWU</td>
</tr>
<tr>
<td>LWU + full shade</td>
<td>MWU + full shade</td>
</tr>
<tr>
<td>Part shade</td>
<td>LWU + part shade</td>
</tr>
<tr>
<td>Full sun</td>
<td>LWU + full sun</td>
</tr>
</tbody>
</table>

5.5 Comparing conventional methods with WASP Module 1

This section presents a comparison of two conventional methods used for estimation of irrigation water requirement with the proposed rational method of WASP Module 1. The irrigation water requirements for the individual landscape components turf and garden bed, corresponding to the nine landscape scenarios, were calculated for soil and climate characteristics of both Kogarah and Penrith. The two conventional methods were:

1. The *landscape coefficient* ($K_L$) method (Costello et al. 2000), whereby monthly or quarterly irrigation budget is calculated as:

$$I_{(month/quarter)} = ET_{L(month/quarter)}$$

where

$$ET_{L(month/quarter)} = K_L \times ETo$$

$$K_L = \text{landscape coefficient} = k_s \times k_{mc} \times k_d$$

$$ETo = \text{reference evapo-transpiration}$$

---

It was assumed that ignoring the trees would not introduce significant error to the irrigation water requirement estimation because trees being deep rooted vegetation, have access to water that drains under the root zone of the turf and shrubs in the neighborhood of trees. Consequently the trees impose relatively lower demand on externally supplied irrigation water compared to the shallow rooted turf and shrubs.
2. The *landscape coefficient plus effective rainfall (KL + Peff) method* (McCabe 2005), whereby monthly or quarterly irrigation budget is calculated as follows:

\[
I_{(\text{month/quarter})} = ET_L(\text{month/quarter}) - \text{REF} \times P_{(\text{month/quarter})}
\]

where

- \(\text{REF} = \) rainfall effectiveness factor, usually considered as 0.5
- \(ET_L(\text{month/quarter}) = KL \times ET_O\)
- \(KL = \) landscape coefficient = \(k_s \times k_{mc} \times k_d\)
- \(ET_O = \) reference evapo-transpiration

In preparing the estimates of landscape irrigation budget derived by the two conventional methods and the estimates derived using the proposed rational method of WASP Module 1:

- The same turf and garden bed coefficients corresponding to each of the nine landscape scenarios, as shown in Table 5-3 and Table 5-4 were used for all three methods.
- In estimating the landscape irrigation budget using the method of WASP Module 1, the median monthly irrigation budget was calculated for individual landscape components, namely turf and garden bed, using the daily irrigation budgets previously calculated for 100 years of daily rainfall and reference evapo-transpiration data.

A comparison of the median monthly irrigation water requirements for turf estimated using the three methods is presented in Figure 5-7.
Figure 5-7: Kogarah (Left) vs. Penrith (Right): Median monthly turf irrigation budgets compared by method.
LWU = low water using; MWU = moderate water using; HWU = high water using.
5.5.1 Turf irrigation budget

Observation of Figure 5-7 reveals the following noteworthy points for the calculated turf irrigation budgets, assuming that the budget calculated by WASP Module 1 is relatively more realistic than other two methods, which are empirical in nature:

- In both Kogarah and Penrith, the $K_L$ method over-estimates the irrigation budget for turf for all three water-use characteristics and all three microclimate scenarios.

- In the case of Kogarah, the $(K_L + P_{eff})$ method under-estimates the irrigation budget for turf for all three water-use characteristics and all microclimate scenarios. In the case of Penrith, the irrigation budget estimated by the $(K_L + P_{eff})$ method tends to be very close to budgets estimated by WASP except in the three scenarios LWU + part-shade ($K_L = 0.6$), LWU + sunny ($K_L = 0.7$) and HWU + sunny ($K_L = 1.0$).

The comparison highlights the fact that the $K_L$ method does not take account of soil characteristics or of rainfall, both of which contribute to the method’s gross over-estimation of irrigation budget for all nine landscape scenarios in both areas.

The comparison also highlights the fact that the $(K_L + P_{eff})$ method does not take account of soil characteristics and therefore under-estimates the irrigation water requirement for turf in sandy soil, notably for Kogarah. This limitation is not as obvious in the case of the clayey soils of Penrith, where WASP Module 1 estimations are very close to those of the $(K_L + P_{eff})$ method. This implies that use of a rational method like WASP Module 1 becomes more critical in areas with sandy soils.

From the viewpoint of developing landscape irrigation budgets to provide water-saving goals in urban irrigation, the $K_L$ method has limited potential to contribute to water-use efficiency because of its non-discriminating output for shallow as well as moderate rooted plantings and for sunny and well-shaded micro-climate. However, the $(K_L + P_{eff})$ method shows some potential for developing water-saving goals for turf growing in clayey soil.
5.5.2 Garden bed irrigation budget

A comparison of the median monthly irrigation budgets for garden beds calculated from the three methods is presented in Figure 5-8.

The following points are noteworthy for the calculated garden bed irrigation budgets, assuming that the budget calculated by WASP Module 1 is relatively more realistic than other two methods, which are empirical in nature:

- For Kogarah, the \((K_L + P_{eff})\) method and WASP are in close agreement for all three water-use characteristics and all microclimate scenarios, except for sunny scenarios corresponding to low, moderate and high water using characteristics, where the \((K_L + P_{eff})\) method over-estimates the irrigation budget. The \(K_L\) method results corresponding to these three scenarios also over-estimate the irrigation budget compared to WASP. The over-estimation is greater for ‘HWU + sunny’, and marginal for ‘LWU + sunny’ and ‘MWU + sunny’.

- For Penrith, the \((K_L + P_{eff})\) method is in close agreement with WASP except for ‘HWU + sunny’, where the \((K_L + P_{eff})\) method grossly over-estimates the irrigation requirement, and for ‘LWU + sunny’, where it marginally over-estimates the budget.

- In other words, except for sunny landscape scenarios, in both Penrith and Kogarah the \((K_L + P_{eff})\) budget is largely in agreement with the WASP budget.

- The ‘sunny’ landscape scenarios resulting in different outputs is reflective of the fact that WASP Module 1 is more responsive to micro-climate factor than the conventional methods. Therefore when the micro-climate factor has a high value (as in case of sunny scenario), the WASP output or response is significantly different from the response of other methods.

- The \(K_L\) method grossly over-estimates the irrigation budget for garden beds for all nine scenarios and in both areas, suggesting that this method has limited potential to contribute to water-saving goals for garden bed irrigation.
The over-estimation of budget by the \((K_l + P_{\text{eff}})\) method is due to the fact that, unlike WASP, it does not take account of the deeper root zone of shrubs, which provides soil water storage allowing greater intervals between irrigation events.
Figure 5-8: Kogarah (Left) & Penrith (Right): Median monthly garden bed irrigation budgets compared by method
LWU = low water using; MWU = moderate water using; HWU = high water using.
5.6 Calculating landscape irrigation budget using WASP Module 1

Prior to calculating the landscape irrigation budgets for the nine landscape scenarios, WASP Module 1 was run for the two landscape components, turf and shrubs (garden bed plants), corresponding to each scenario, using 100-year daily rainfall and reference ET data.

Reference ET was modified prior to running the module for estimation of water requirements by multiplying it with the turf coefficient and shrub coefficient respectively. The turf and shrub coefficients are obtained by multiplying the water-use factor $k_s$ and microclimate factor $k_{mc}$ (see Table 5-3 and Table 5-4). The plant density $k_d$ of turf and shrubs was assumed to be moderate for all nine scenarios (i.e. $k_d = 1$), and is implicit in the determination of the coefficient values.

Table 5-3: Turf ET coefficient corresponding to the 9 landscape scenarios shown in the Table have been obtained as product of $k_{mc}$ and $k_s$; Values of $k_{mc}$ and $k_s$ have been used as given in McCabe et al. 2005.

<table>
<thead>
<tr>
<th>Turf coefficient</th>
<th>Water use factor ($k_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low (0.6)</td>
</tr>
<tr>
<td>Microclimate factor ($k_{mc}$)</td>
<td>Full shade (0.8)</td>
</tr>
<tr>
<td></td>
<td>Part shade (1.0)</td>
</tr>
<tr>
<td></td>
<td>Full sun (1.2)</td>
</tr>
</tbody>
</table>

Table 5-4: Garden bed ET coefficient corresponding to the 9 landscape scenarios shown in the Table have been obtained as product of $k_{mc}$ and $k_s$; Values of $k_{mc}$ and $k_s$ have been used as given in McCabe et al. 2005.

<table>
<thead>
<tr>
<th>Garden bed coefficient</th>
<th>Water use factor ($k_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low (0.2)</td>
</tr>
<tr>
<td>Microclimate factor ($k_{mc}$)</td>
<td>Full shade (0.5)</td>
</tr>
<tr>
<td></td>
<td>Part shade (1.0)</td>
</tr>
<tr>
<td></td>
<td>Full sun (1.3)</td>
</tr>
</tbody>
</table>
WASP Module 1 output, the daily irrigation water requirement for turf and garden bed corresponding to each day of the financial years 1906–2005 was sorted with the view to:

- compiling daily data corresponding to the 100 years
- Determining the median monthly values of irrigation water requirements for each landscape component.

Landscape irrigation budget was then calculated as a weighted average of the irrigation budget of turf and garden bed, the weighting factor being the respective area of turf and garden bed making up the domestic garden. The median monthly values obtained from the daily soil water balance run for the individual components over the 100-year data were used for the landscape irrigation budgets, which were calculated for landscapes with different percentages of turf areas. Figure 5-9 shows an example of quarterly landscape irrigation budget plots in Kogarah for low water using domestic gardens with different percentages of turf areas. In the figure, 0% turf area implies that the garden is entirely made of shrubs, i.e. 100% of the garden area is shrubs; 60% turf area implies 40% of the garden is made up of garden shrubs; 100% turf area implies that the entire garden is made up of turf.

![Figure 5-9: Example of a linear plot to calculate quarterly landscape irrigation budgets in Kogarah](image-url)
Quarterly graphs were plotted for each of the nine landscape scenarios and used for calculating the landscape irrigation budget for gardens of a given landscape composition (% turf and % garden bed), microclimate and water use characteristics. The graphs corresponding to all nine landscape scenarios for Kogarah and Penrith are included in Appendix 1.

5.7 Comparing landscape irrigation budgets for Kogarah and Penrith

5.7.1 Low water using (LWU) domestic gardens

Figure 5-10 displays the quarterly irrigation budgets for low water using landscapes for three microclimate scenarios in Penrith and Kogarah; with 0%, 50% and 100% turf area.

![Figure 5-10: Low water using (LWU) landscape irrigation budgets compared by region and microclimate](image)

The following points are noteworthy about low water using (LWU) landscapes in both areas:
Penrith:
• Fully shaded LWU domestic gardens which have no turf area and are entirely (100%) composed of low water using plant species do not require any external application of irrigation water.
• The annual landscape irrigation budget for LWU gardens with turf varies from 6% of reference ET (shade) to 34% of reference ET (full sun).
• LWU gardens can contribute to a reduction in water demand proportional to the reduction in the lawn area. Substituting half the lawn area with LWU garden shrubs contributes to 50% reduction in water demand.
• Modifying the microclimate conditions can also contribute to reduction in water demand. For example, partly shading a garden (with 100% turf) which is exposed to full sun, using natural or artificial sun screens, can reduce water demand by about 23%. Converting a partly shaded garden (with 50% turf) to a fully shaded one reduces water demand by 57%. Greater savings are achieved by shading gardens with a greater proportion of turf.

Kogarah:
• Fully shaded LWU domestic gardens which have no turf area and are entirely (100%) composed of low water using plant species do not require any external application of irrigation water.
• The annual landscape irrigation budget for LWU gardens with turf varies from 14% of reference ET (shade) to 45% of reference ET (full sun).
• Reducing the proportion of lawn by substituting it with a LWU garden shrub bed can contribute to a reduction in water demand which is proportional to reduction in the lawn area. Substituting half the lawn area with LWU garden shrubs contributes to 50% reduction in water demand.
• Modifying the microclimate conditions can also contribute to reduction in water demand. For example, partly shading a garden with 50% turf which is exposed to full sun, using natural or artificial sun screens, can reduce water demand by about 9%. Converting a partly shaded garden with 50% turf to a fully shaded one reduces water demand by 25%. Greater savings are achieved for gardens with a greater proportion of turf.
5.7.2 Moderate water using (MWU) domestic gardens

Figure 5-11 displays the landscape irrigation budgets for moderate water using (MWU) landscapes for three microclimate scenarios in Penrith and Kogarah; with 0%, 50% and 100% turf area.

Figure 5-11: Moderate water using (MWU) landscape irrigation budgets compared by region and microclimate

The following points are noteworthy about the moderate water using (MWU) landscapes in both areas:

Penrith:
- The annual landscape irrigation budget for MWU gardens without turf varies from 5% of reference ET (shade) to 25% of reference ET (full sun).
- The annual landscape irrigation budget for MWU gardens with turf varies from 16% of reference ET (shade) to 45% of reference ET (full sun).
- Reducing the proportion of lawn (by substituting it with MWU garden shrubs) can contribute to a reduction in water demand which is proportional to reduction in the lawn area. For example, substituting half the lawn area in a MWU domestic garden with MWU garden shrubs contributes to a 15–40% reduction in water demand, depending on the microclimate of the lawn section being substituted. Greater savings are achieved in a fully shaded garden.
• Modifying the microclimate conditions can also contribute to reduction in water demand. For example, partly shading the MWU garden which is exposed to full sun, using natural or artificial sun screens, can reduce water demand by about 29%. Converting a partly shaded garden (with 50% turf) to a fully shaded one reduces water demand by 41%. Greater savings are achieved for gardens with greater proportions of turf.

Kogarah:
• The annual landscape irrigation budget for MWU gardens without turf varies from 5% of reference ET (shade) to 25% of reference ET (full sun).
• The annual landscape irrigation budget for MWU gardens with turf varies from 21% of reference ET (shade) to 54% of reference ET (full sun).
• Reducing the proportion of lawn by substituting it with MWU garden shrubs can contribute to a reduction in water demand which is proportional to reduction in the lawn area. For example, substituting half the lawn area in a MWU domestic garden with MWU garden shrubs contributes to a 21–43% reduction in water demand, depending on the microclimate of the turf area being substituted. Greater savings are achieved in a fully shaded garden.
• Modifying the microclimate conditions can also contribute to reduction in water demand. For example, partly shading the MWU garden which is exposed to full sun, using natural or artificial sun screens, can reduce water demand by about 21%. Converting a partly shaded garden (with 50% turf) to a fully shaded one reduces water demand by 34%. Greater savings are achieved for gardens with a greater proportion of turf.

5.7.3 High water using (MWU) domestic gardens
Figure 5-12 displays the quarterly irrigation budgets for high water using landscapes for the three microclimate scenarios in Penrith and Kogarah; with 0%, 50% and 100% turf area.
Figure 5-12: High water using (HWU) landscape irrigation budgets compared by region and microclimate

The following points are noteworthy about high water using (HWU) landscapes in the two areas:

**Penrith:**

- The annual landscape irrigation budget for HWU gardens without turf varies from 11% of reference ET (shade) to 30% of reference ET (full sun).
- The annual landscape irrigation budget for HWU gardens with turf varies from 19% of reference ET (shade) to 63% of reference ET (full sun).
- Reducing the proportion of lawn by substituting it with HWU garden shrubs can contribute to a reduction in water demand which is proportional to reduction in the lawn area. For example, substituting half the lawn area in an HWU domestic garden with HWU garden shrubs contributes to a 25–29% reduction in water demand, depending on the microclimate of the turf area being substituted. Greater savings are achieved in a fully shaded garden.
- Modifying the microclimate conditions can also contribute to reduction in water demand. For example, partly shading the HWU garden which is exposed to full sun, using natural or artificial sun screens, can reduce water demand by about 28%. Converting a partly shaded garden (with 50% turf) to a fully
shaded one reduces water demand by 44%. Greater savings are achieved for gardens with greater proportions of turf.

Kogarah:

- The annual landscape irrigation budget for HWU gardens without turf varies from 11% of reference ET (shade) to 44% of reference ET (full sun).
- The annual landscape irrigation budget for HWU gardens with turf varies from 24% of reference ET (shade) to 71% of reference ET (full sun).
- Fully shaded HWU domestic gardens with no turf and composed entirely of MWU garden shrubs do not require any external application of irrigation water during the April–June quarter, Q4, and July–September quarter, Q1.
- Reducing the proportion of lawn by substituting it with HWU garden shrubs can contribute to a reduction in water demand which is proportional to reduction in the lawn area. For example, substituting half the lawn area in a HWU domestic garden with HWU garden shrubs contributes to a 19–35% reduction in water demand, depending on the microclimate of the turf area being substituted. Greater savings are achieved in a fully shaded garden.
- Modifying the microclimate conditions can also contribute to reduction in water demand. For example, partly shading the HWU garden which is exposed to full sun, using natural or artificial sun screens, can reduce water demand by about 59%. Converting a partly shaded garden (with 50% turf) to a fully shaded one reduces water demand by 49%. Greater savings are achieved for gardens with greater proportions of turf.

5.7.4 Comparison of Soil-Climate Zones

In comparing the landscape irrigation budgets for domestic gardens in Penrith and Kogarah, it is noteworthy that the irrigation budgets for gardens in Penrith are lower than those for domestic gardens in Kogarah for all landscape scenarios except for fully shaded where, in both suburbs, the LWU garden requires no irrigation in any season. The lower irrigation budget for Penrith is because of the clayey soil which has a greater water-holding capacity than the sandy soils of Kogarah. The water-holding capacity of the clayey soil accords the landscape a buffer and storage for soil water which plants can draw upon during periods when evapo-transpiration exceeds rainfall. This results in reduced need for externally supplied irrigation water.
5.8 Chapter Summary

The landscape irrigation budgets for turf and garden bed corresponding to nine landscape scenarios were estimated for Kogarah and Penrith, using WASP Module 1 and two empirical methods commonly used by turf and public open space irrigation managers. The findings can be summarised as follows:

- The empirical \( (K_L + P_{eff}) \) method for estimation of irrigation budgets takes account of rainfall and ET, but does not account for the water-holding capacity of the soil and the root zone depth of the plant. Because of this limitation the \( (K_L + P_{eff}) \) method under-estimates the budget for plants growing in sandy soil and over-estimates the irrigation budget for plants exposed to sunny microclimates and for garden bed plants which have a deeper root zone depth compared to turf.

- The empirical \( K_L \) method does not take account of rainfall, soil characteristics or the root zone depth of the plant. It thus tends to over-estimate the budget for all types of plants under all microclimates.

- Using empirical methods for estimating the irrigation budget carries the risk of either not providing the water required for sustaining the turf by under-watering \( (K_L + P_{eff} \text{ method for turf in sandy soil}) \) or wasting the water by over-watering \( K_L \) method). This suggests a rational approach for estimating landscape irrigation budget is necessary for sustainable irrigation of turf, where both turf and water are managed in a sustainable manner.

Having demonstrated the rational approach of WASP, taking account of rainfall, ET, soil characteristics and plant characteristics, the landscape irrigation budgets were estimated for low, moderate and high water using landscapes having different compositions (% turf area) and microclimate exposure in Kogarah and Penrith. A comparison of the budgets for the landscapes in the two regions representing different soil–climate characteristics showed that the budgets developed using WASP were commensurate with soil and climate variation and therefore have the capacity to be used as irrigation benchmarks that are reflective of soil, climate and plant
characteristics after validating this finding using soil parameter values based on actual soils rather than assumed values.

The next chapter demonstrates how the landscape irrigation budget can be used to estimate the water-saving potential of existing domestic gardens, using the metered water consumption data for the case study domestic garden sites in Kogarah and Penrith, and evaluates the effectiveness of demand management policies aimed at urban irrigation such as water restrictions.

6.1 Introduction

Demand management strategy forms an integral part of any sustainable water management strategy. Realising the most of demand management potential for all end uses is what makes a demand management strategy effective in contributing to its objective of achieving reduction in demand. Demand management can be looked at as making a new source of water available, whether through reducing the overall demand for water through improved efficiency, or through the substitution of potable water with alternative sources such as stormwater, rainwater, grey water or treated effluent for irrigation uses.

In Sydney, in the case of potable (indoor) water, the market penetration of water-efficient appliances and/or a retrofit or rebate program is being monitored to determine the demand management potential that has been achieved and remains to be achieved (DECC 2007).

When it comes to outdoor water demand and urban irrigation demand in particular, it is common to find references to the level of water efficiency or percentage savings that can be achieved or are likely to be achieved by certain watering equipment or a demand management program. However, the percentage water savings or level of water efficiency achievable cannot, on their own, indicate the demand management potential of the urban irrigation demand. This is because demand management potential of urban irrigation is a function of the landscape, its composition and the characteristics of the soil–climate zone in which the landscape is located. Without a benchmark or budget that takes into account these complexities, it is impossible to measure and evaluate the urban irrigation demand management potential that has been achieved or remains to be achieved.\textsuperscript{18} In order to drive this point more clearly, a

\textsuperscript{18} Human behaviour in terms of how people design, manage and maintain their gardens and irrigation systems influences the reduction in urban irrigation demand that is potentially achievable, and needs to be taken into account in designing a demand management program. However, it is neither feasible, nor necessary to take account of human behaviour when determining the theoretical maximum limit or
discussion about the outdoor demand management program called the Landscape Assessment Program, as developed by Sydney Water Corporation follows.

In the recently developed 2006 Sydney Metropolitan Water Plan (see Figure 6-1) a water savings target of 24 billion litres was set for residential outdoor water use, out of a projected total of 145 billion litres per year of water savings, to be achieved by 2015. To understand this in the context of Sydney’s overall residential water demand, the following facts need to be understood.

- **Setting an arbitrary water savings target:** The Metro Water Plan assumes that the Landscape Assessment Program is likely to achieve 15% reduction in outdoor demand, without explicitly stating or making clear the basis for the assumption.

![Figure 6-1: Sydney Metropolitan Water Plan Source: 2006 Sydney Metropolitan Water Strategy](image)

- **Setting arbitrary targets for implementation of the program:** The Metro Water Plan aims to complete a Landscape Assessment Program of 40,000 houses by potential for demand management of an end use such as garden and lawn watering, which would serve as a benchmark against which the effectiveness of a demand management program could be measured.
2015. However, the program in its current form does not incorporate any evaluation framework or rationale to evaluate its effectiveness in terms of the demand management potential to be realised in the form of actual water savings. Landscape assessments, by themselves, cannot translate into water savings unless the findings of the assessments are implemented by residents.

For these reasons, to evaluate the effectiveness of such a large-scale capital intensive demand management program, a framework must be available.

In relation to Sydney’s Metro Water Plan, the crucial questions are:

What is the maximum outdoor demand management potential?

and:

What proportion of the maximum outdoor demand management potential is represented by the target of 24 billion litres per year?

These questions call for a framework to evaluate the effectiveness of the dollar-intensive outdoor demand management programs being developed to obtain the targeted water savings. To answer and address such questions, this thesis argues that:

- It is possible to get a realistic estimate of the outdoor demand management potential using a scientific rationale to measure/quantify landscape irrigation budgets.
- A rational estimate of outdoor demand management potential can help in setting realistic demand management and water saving targets.
- A rational estimate of outdoor demand management potential can help in evaluating the effectiveness of water saving actions or policies on the basis of the percentage of total outdoor demand management potential achieved.

In the previous chapters, the concept of landscape irrigation budgets was introduced and their values estimated for domestic gardens in Kogarah and
Penrith suburbs. This chapter explores and demonstrates further how the landscape irrigation budget can be used for: estimating the *water saving potential* of existing domestic gardens; and *evaluating the effectiveness* of water-saving actions and measures, using mandatory water restrictions as an example.

Both the above applications are ultimately aimed at answering the following key questions pertaining to management of urban irrigation demand with reference to domestic gardens:

- How much water can potentially be saved on existing, established suburban gardens?
- What is the distribution of the existing domestic gardens based on their water saving potential? In other words, what proportions of existing gardens in a given suburb have high, moderate, low and no water saving potential?
- How effective has the water restriction policy been in realising the water saving potential of domestic gardens?
- How much water saving potential remains to be realised over and above what has been realised by the policy of water restriction?

The answers to these questions have the potential to inform policies and programs aimed at reducing the demand and/or saving water on existing landscapes, in the following ways:

- by enabling a comparison of policies and programs, prior to implementation, on the basis of the volume of water they can potentially save;
- by enabling the policies and programs to be specifically tailored for landscapes of different water saving potential;
- by targeting the policies and programs at a particular location knowing the water saving potential of the landscapes in the location; and

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19 High water saving potential is indicative of low water use efficiency; *moderate* water saving potential indicates moderate water use efficiency; *low* water saving potential is indicative of high water use efficiency; and *no* water saving potential indicates no or minimal potable water use or the presence of a wholly rain-fed garden.
by evaluating the policies and programs, post implementation, to determine the effectiveness (the volume of water that was actually saved) of the programs.

This chapter demonstrates how landscape irrigation budget can be used for answering the above questions for existing urban landscapes, using a selection of domestic gardens located in the Sydney metropolitan areas of Kogarah and Penrith as case studies. It is based on Module 2 of the WASP framework (see Figure 6-2).

Figure 6-2: This chapter is focused on Module 2 of the WASP framework

The chapter begins with a description of the various steps involved in the process of estimating the water saving potential (WaSP) of existing landscapes. This is followed by a discussion about the input data used to estimate the water saving potential in a selection of domestic gardens in Kogarah and Penrith and to evaluate the effectiveness of water restrictions in achieving the water saving potential of those gardens.

The chapter concludes with a presentation and discussion of the following results with respect to each of the two applications of landscape irrigation budget:
volume of irrigation water applied on the domestic gardens surveyed;
water saving potential of the domestic gardens surveyed;
distribution of the domestic gardens surveyed by their level of water saving potential, i.e. high, moderate, low and none;
water saving potential of the gardens before water restrictions;
water saving potential of the gardens after water restrictions.

6.2 Estimating water saving potential of landscapes: The steps involved

This section describes the various steps involved in the process of estimating the water saving potential of established and existing landscapes in a given soil–climate zone. Figure 6-3 gives a schematic representation of the six main steps. In sections 6.3-6.8, each of the six steps is described as they were undertaken.
Figure 6-3: Six steps involved in estimating water saving potential

1. **STEP 1**: (see Chapter 4) Selecting the landscapes from the population
2. **STEP 2**: (see Chapter 4) Characterising the landscapes
3. **STEP 3**: Estimating the historically applied irrigation rate (mm)
4. **STEP 4**: Estimating the water saving potential (WaSP) of landscapes
5. **STEP 5**: % area distribution of the landscapes by their WaSP
6. **STEP 6**: Mapping the landscapes by their WaSP

Geo-coded aerial photos of landscapes
6.3 Estimating the volume of irrigation water historically applied

Historical metered water consumption data is held by water service providers. Consumption data for residential properties are recorded for billing purposes on a quarterly basis each financial year. For non-residential properties, historical metered water consumption records are held on a monthly basis.

The quarterly irrigation volume applied on the domestic garden by each property is determined by making the following assumptions:

1. Consumption in the minimum quarter corresponds to indoor water demand. This concurs with Western Australian studies which have taken a similar approach in extracting outdoor water use from metered water consumption data of a residential property (Water Authority of Western Australia 1987; Loh and Coghlan 2003). In Sydney, as in Perth, the quarter corresponding to winter tends to have high rainfall and low evapo-transpiration and consequently almost no irrigation water is applied. Thus for the purpose of residential water demand modelling for this research, indoor water use for a property was assumed to be equal to its consumption corresponding to the minimum quarter.

2. Consequent to assumption 1, outdoor demand for each of the other three quarters is equal to the difference between the minimum quarter and the total household water consumption for those quarters.

3. A proportion of outdoor consumption is attributed to garden watering. Outdoor consumption is made up of garden watering, water used for washing the car, hosing of paved areas, topping up the swimming pool and the operation of evaporative air conditioners. Except in the case of hot and arid (tropical) climate zones, 90–95% of outdoor water use is attributable to garden irrigation (Vickers 2001; Gleick et al. 2003). For this research, 90% of estimated outdoor consumption was assumed to be equal to the volume of irrigation water applied on the gardens.
6.3.1 Practical considerations in obtaining metered consumption data
For this research, the metered water consumption data for the selected properties were obtained from Sydney Water Corporation, the water service provider to the single detached dwellings in Kogarah and Penrith. There were two significant practical issues which were given due consideration while requesting the historical metered water consumption data of 222 SDDs in Kogarah and 192 SDDs in Penrith from Sydney Water Corporation.

Availability of data in financial year quarters
Sydney Water Corporation (SWC) bills its residential customers every quarter of the financial year. This meant that the data was available as shown in Table 6-1.

Table 6-1: Financial year quarters and predominant season

<table>
<thead>
<tr>
<th>Quarter #</th>
<th>Months in quarter</th>
<th>Predominant season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarter 1</td>
<td>July–September</td>
<td>Winter–spring</td>
</tr>
<tr>
<td>Quarter 2</td>
<td>October–December</td>
<td>Spring–summer</td>
</tr>
<tr>
<td>Quarter 3</td>
<td>January–March</td>
<td>Summer–autumn</td>
</tr>
<tr>
<td>Quarter 4</td>
<td>April–June</td>
<td>Autumn–winter</td>
</tr>
</tbody>
</table>

SWC obligation for maintaining privacy of residents
Owing to the obligation of the water service provider to maintain the privacy of their customers, SWC was unable to provide the historical metered consumption data for individual properties unless consent was received from every property forming the selection of domestic gardens. Obtaining consent from approximately 400 property owners was not feasible within the time available for research, and SWC was requested to provide combined historical metered consumption data for two or three SDDs. This strategy was effective because:

- it allowed SWC to provide the data without breaching their contractual obligations; and
- the ultimate aim of the analysis was to estimate the water saving potential of the domestic gardens aggregated at regional scale rather than at individual garden scale. This meant that estimating the water saving potential for a set of
two or three properties would still serve the purpose of estimating aggregate water saving potential.

**Periods of water restriction**

SWC has enforced water restrictions for residential clients from 2003, which continue to the present date. Table 6-2 shows the different levels of water restrictions corresponding to different periods from 2003 to date. As shown in Table 6-3, the metered consumption data of the SDDs for the research thus comprised:

- six years of quarterly metered water consumption data before water restrictions were imposed, i.e. from financial year (FY) 1997/1998 to FY 2001/2002; and
- four years of quarterly metered water consumption data after water restrictions were imposed, i.e. from FY 2002/2003 to FY 2006/2007.

**Table 6-2: Water restriction regimes enforced by Sydney Water Corporation**

<table>
<thead>
<tr>
<th>Period</th>
<th>Level of water restriction</th>
<th>Nature of restriction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 October 2003–31 May 2004</td>
<td>Level 1</td>
<td>• No sprinklers allowed at any time; drip irrigation and hand-held hoses allowed any time.</td>
</tr>
<tr>
<td>1 June 2004–31 May 2005</td>
<td>Level 2</td>
<td>• No sprinklers allowed at any time; drip irrigation and hand-held hoses allowed any time 3 days per week.</td>
</tr>
<tr>
<td>1 June 2005 to present</td>
<td>Level 3</td>
<td>• Hand-held hosing and drip irrigation allowed only on Wednesdays and Sundays before 10 am and after 4 pm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No sprinklers or other watering systems to be used at any time.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• A permit from Sydney Water is required to fill new or renovated pools bigger than 10,000 litres.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No hosing of hard surfaces, including vehicles, at any time.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No hoses or taps to be left running unattended except when filling pools or containers.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fire hoses must only be used for fire fighting purposes, not for cleaning.</td>
</tr>
</tbody>
</table>

*Source: 2006 Sydney Metropolitan Water Plan*

<table>
<thead>
<tr>
<th>Financial year</th>
<th>Quarter #</th>
<th>Water restriction level</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5 years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002/2003</td>
<td>Quarters 1–4</td>
<td>None</td>
</tr>
<tr>
<td>(1 year)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003/2004</td>
<td>Quarter 1</td>
<td>None</td>
</tr>
<tr>
<td>(1 year)</td>
<td>Quarters 2, 3</td>
<td>Level 1</td>
</tr>
<tr>
<td></td>
<td>Quarter 4</td>
<td>Levels 1, 2</td>
</tr>
<tr>
<td>2004/2005</td>
<td>Quarters 1–3</td>
<td>Level 2</td>
</tr>
<tr>
<td>(1 year)</td>
<td>Quarter 4</td>
<td>Levels 2, 3</td>
</tr>
<tr>
<td>2005/2006 (1 year)</td>
<td>Quarters 1–4</td>
<td>Level 3</td>
</tr>
</tbody>
</table>

6.4 Estimating water saving potential of case study garden sites

Estimating the water saving potential of the case study garden sites involved comparing the irrigation water applied on the individual landscape with the irrigation budget corresponding to a given water saving scenario. The irrigation budget corresponding to the LWU garden, as estimated in Chapter 5 (and as shown in Table 6-4: Irrigation budget for low water using (LWU) garden in Penrith for Penrith), was estimated for the individual gardens in this category by taking account of their microclimate and percentage turf area (nine sub-categories) and plotted as in Figure 6-4.

Table 6-4: Irrigation budget for low water using (LWU) garden in Penrith

<table>
<thead>
<tr>
<th>PENRITH: Landscape Irrigation Budget for Low Water Using Garden (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Turf</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>Full Shade</td>
</tr>
<tr>
<td>0%</td>
</tr>
<tr>
<td>50%</td>
</tr>
<tr>
<td>100%</td>
</tr>
<tr>
<td>Part Shade</td>
</tr>
<tr>
<td>0%</td>
</tr>
<tr>
<td>50%</td>
</tr>
<tr>
<td>100%</td>
</tr>
<tr>
<td>Full Sun</td>
</tr>
<tr>
<td>0%</td>
</tr>
<tr>
<td>50%</td>
</tr>
<tr>
<td>100%</td>
</tr>
</tbody>
</table>
6.5 Estimating % area distribution of gardens by their water saving potential

To estimate the water saving potential of individual landscapes involved the following steps:

- determining the quarterly water saving potential (in mm) for all gardens in the study
- calculating the annual water saving potential (in mm) for all gardens by adding up the quarterly water saving potentials;
- sorting the gardens by their annual water saving potential (mm);
- classifying the gardens as having High, Moderate, Low or No water saving potential on the basis of the classification appearing in Table 6-5;
- adding up the total landscape area of gardens in each of the water saving potential categories (High WaSP, Moderate WaSP, Low WaSP and No WaSP); and
- calculating the landscape area in each category expressed as a proportion or percentage of the total landscape area of the selected gardens.
Table 6-5: Defining High, Moderate and Low water saving potential

<table>
<thead>
<tr>
<th>Classification</th>
<th>Water Saving Potential Level</th>
<th>Annual Irrigation Rate Exceeds Annual Landscape Irrigation Budget by</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWaSP</td>
<td>High</td>
<td>&gt;250mm</td>
</tr>
<tr>
<td>MWaSP</td>
<td>Moderate</td>
<td>51-250mm</td>
</tr>
<tr>
<td>LWaSP</td>
<td>Low</td>
<td>11-50mm</td>
</tr>
<tr>
<td>NWaSP</td>
<td>None</td>
<td>&lt;10mm</td>
</tr>
</tbody>
</table>

6.6 Results and discussion:

6.6.1 Water use characteristics of gardens in Kogarah and Penrith when water restrictions did not apply

The metered water consumption data were analysed for 111 pairs of single detached dwellings (SDDs) in Kogarah and for 96 pairs of SDDs in Penrith (Table 6-6). The data corresponded to the garden sites selected, grouped and characterised in Chapter 4.

This section and Section 6.8 discuss the analysis of the metered consumption data for the financial years 1997/1998 to 2002/2003, when no water restrictions were in place, which was intended to:

- determine the water use characteristics of the surveyed gardens;
- estimate the water saving potential of individual gardens; and
- estimate the percentage area distribution of the surveyed gardens by their water saving potential.
Table 6-6: Landscape and water use characteristics of Kogarah and Penrith gardens

<table>
<thead>
<tr>
<th>Landscape Area, sq.m</th>
<th>% Turf Area</th>
<th>Total Household Water Use, kL/annum/house</th>
<th>Applied Irrigation, kL/annum/house</th>
<th>% of total household water use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>KOGARAH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>143</td>
<td>64%</td>
<td>272</td>
<td>43</td>
</tr>
<tr>
<td>Min</td>
<td>25</td>
<td>0%</td>
<td>132</td>
<td>0</td>
</tr>
<tr>
<td>Max</td>
<td>328</td>
<td>100%</td>
<td>708</td>
<td>129</td>
</tr>
<tr>
<td>SD</td>
<td>119</td>
<td>24%</td>
<td>216</td>
<td>44</td>
</tr>
<tr>
<td><strong>PENRITH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>168</td>
<td>77%</td>
<td>282</td>
<td>49</td>
</tr>
<tr>
<td>Min</td>
<td>63</td>
<td>35%</td>
<td>93</td>
<td>0</td>
</tr>
<tr>
<td>Max</td>
<td>1147</td>
<td>100%</td>
<td>570</td>
<td>158</td>
</tr>
<tr>
<td>SD</td>
<td>244</td>
<td>15%</td>
<td>238</td>
<td>58</td>
</tr>
</tbody>
</table>

Average (mean) household water use for the properties surveyed in Kogarah was 272 kL per annum, and 282 kL per annum for the properties surveyed in Penrith (See Table 6-6 and Figures 6-5, 6-6 and 6-7). Kogarah gardens used an average 17% of total household water use, for irrigation. In Penrith, the average irrigation volume was equivalent to 16% of total household water use.

Figure 6-5: Water use characteristics of domestic gardens in Kogarah for period FY 1997/1998 to FY 2002/2003, when there were no water restrictions
Figure 6-6: Water use characteristics of domestic gardens in Penrith for period FY 1997/1998 to FY 2002/2003, when there were no water restrictions
Comparing these results with those of other domestic water use studies, the Australian Water Account 2000–01 (ABS 2004) reported that, on average, households in New South Wales consumed 250 kL per year in 2001 and that 25% of this consumption
was for outdoor purposes. The Independent Pricing and Regulatory Tribunal (IPART) study of 2004 estimated that households in separate dwellings used, on average, 13% of their consumption on the garden (IPART 2004). The average garden watering use of 16% and 17% of total household water use in the surveyed gardens of Kogarah and Penrith respectively is within the range of 13% (IPART study) to 25% (ABS study).

Nonetheless, irrigation water use varied in quantity over a wide range, from nil to 129 kL/hh/annum (in Kogarah), and nil to 158 kL/hh/annum (in Penrith), with average use about 50 kL/hh/annum. According to the 2006 Metropolitan Water Plan, the average Sydney household uses 70 kL/hh/annum for irrigation purposes. In the Australian Water Account 2000–01 study, the average outdoor water use per household was 63 kL/hh/annum, based on 25% of 250 kL total water use per household per year. In other words, the average irrigation water use on the case study garden sites is lower than the figures estimated by those two studies.

6.6.2 Water saving potential when water restrictions did not apply

The analysis revealed the following:

- As shown in Table 6-7, the mean water saving potential per household was found to be moderate (51-250mm per annum, as per the definition in Table 6-5) for both Kogarah and Penrith.
- Water saving potential (WaSP) vs. landscape area (Figure 6-8): In both Kogarah and Penrith, the water saving potential increased with decrease in landscape area, demonstrating that the gardens with small areas tend to overwater and thus represent gardens with high and moderate water saving potential (HWaSP and MWaSP). Determining why this is the case was beyond the scope of this research. However, it is a topic that warrants further research.
- Water saving potential per house and percentage distribution (Figure 6-9):
  - Overall, almost a quarter of the garden sites surveyed had a high water saving potential (HWaSP), with Kogarah at 28% and Penrith at 24%.
  - Garden sites having moderate water saving potential (MWaSP) were the greatest in proportion, at 34% in Kogarah and 45% in Penrith.
For HWaSP gardens, average water saving potential per house was as high as 48 kL/house/annum in Kogarah and 51 kL/house/annum in Penrith.

For MWaSP gardens, average water saving potential per house is 20 kL/house/annum in Kogarah and 19 kL/house/annum in Penrith.

Table 6-7: Water saving potential of case study domestic garden sites in Kogarah and Penrith for period when there were no water restrictions

<table>
<thead>
<tr>
<th>FY 1997-1998 to FY 2002-2003 (NO WATER RESTRICTIONS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation Application Rate, mm/annum</td>
</tr>
<tr>
<td>------------------------------------------------------</td>
</tr>
<tr>
<td><strong>KOGARAH</strong></td>
</tr>
<tr>
<td>Number of surveyed gardens = 222</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
</tr>
<tr>
<td>398</td>
</tr>
<tr>
<td>Min</td>
</tr>
<tr>
<td>Max</td>
</tr>
<tr>
<td>SD</td>
</tr>
<tr>
<td><strong>Penrith</strong></td>
</tr>
<tr>
<td>Number of surveyed gardens = 192</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
</tr>
<tr>
<td>323</td>
</tr>
<tr>
<td>Min</td>
</tr>
<tr>
<td>Max</td>
</tr>
<tr>
<td>SD</td>
</tr>
</tbody>
</table>

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Figure 6-8: Kogarah (top) and Penrith (bottom): Water saving potential vs. landscape area of paired garden sites (based on metered consumption data for period when there were no water restrictions)
Figure 6-9: Percentage area distribution of gardens and their average water saving potential: Kogarah vs. Penrith
6.6.3 Evaluating effectiveness of water restrictions

The historical metered water consumption data for the properties discussed in sections 6.8 and 6.9, both before and after the water restrictions, were analysed to evaluate the effectiveness of water restrictions on:

- annual irrigation application rate (irrigation volume per unit area of garden) (Figure 6-10);
- annual water saving potential per house (Figure 6-11); and
- percentage area distribution of gardens by water saving potential (Figure 6-12).

Table 6-8: Irrigation application rate and water saving potential of Kogarah and Penrith gardens, before and after water restrictions

<table>
<thead>
<tr>
<th></th>
<th>BEFORE WATER RESTRICTIONS</th>
<th>AFTER WATER RESTRICTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irrigation Application Rate, mm/annum</td>
<td>Water Saving Potential, mm/annum</td>
</tr>
<tr>
<td>KOGARAH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>398</td>
<td>230</td>
</tr>
<tr>
<td>Min</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Max</td>
<td>2106</td>
<td>1824</td>
</tr>
<tr>
<td>SD</td>
<td>339</td>
<td>307</td>
</tr>
<tr>
<td>Number of surveyed gardens</td>
<td>222</td>
<td></td>
</tr>
<tr>
<td>PENRITH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>323</td>
<td>176</td>
</tr>
<tr>
<td>Min</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Max</td>
<td>1443</td>
<td>1134</td>
</tr>
<tr>
<td>SD</td>
<td>244</td>
<td>212</td>
</tr>
<tr>
<td>Number of surveyed gardens</td>
<td>192</td>
<td></td>
</tr>
</tbody>
</table>

Based on the analysis, the effectiveness of water restrictions can be evaluated as follows:

- As can be seen from Table 6-8, for both Kogarah and Penrith, despite the reduction achieved in the average water saving potential per household, it remained in the moderate range (51-250 mm/per annum) during water restrictions indicating further scope for water saving potential.
- Based on the reduction in applied irrigation rate (Figure 6-10): For most of the domestic gardens in both suburbs, the irrigation application rates during
water restrictions were generally lower than the irrigation applied before restrictions. Some noteworthy findings were:

- Reduction in irrigation application rate varied widely from house to house, as is evident from the high standard deviation value of the irrigation application rate after the restrictions (Table 6-8).
- For some of the households which had before-restrictions irrigation rates in the middle and lower range values, the irrigation application rate increased instead of decreasing during water restrictions. This shows that while the water restrictions tend to reduce the irrigation application rate of high-intensity garden irrigators, it has an opposite effect on those with low–medium irrigation application rate.

- **Based on the water saving potential (WaSP) tapped from the total potential** (Figure 6-11):
  - Water restrictions have been effective in realising 43% of the water saving potential that existed before water restrictions were imposed in the HWaSP gardens surveyed in Kogarah. In the HWaSP gardens surveyed in Penrith, 56% of the water saving potential has been realised from water restrictions. Conversely, 57% of the water saving potential remains untapped in the HWaSP gardens of Kogarah, despite water restrictions. In Penrith, 44% of water saving potential remains unrealised following water restrictions.
  - Water restrictions effectively realised 51% of the water saving potential that existed in the MWaSP gardens surveyed in Kogarah before the restrictions. However, in Penrith, only 18% of the water saving potential of the MWaSP gardens was realised by water restrictions; here the remaining 82% of water saving potential remains untapped.
  - The total water saving potential of the surveyed gardens of Kogarah is equivalent to 49% of the irrigation demand level that existed before water restrictions. Water restrictions achieved a 33% reduction in irrigation demand, with 16% remaining untapped. Most of the remaining water saving potential, which is equivalent to a further 16%
reduction in irrigation demand, exists in the HWaSP gardens, which constituted 8% of the total gardens surveyed in Kogarah.

- In the surveyed gardens of Penrith, a reduction of 29% was achieved out of the total water saving potential, which is equivalent to 48% reduction in irrigation demand (before water restrictions). Another 19% of savings remain untapped, most of which are to be found in the HWaSP gardens of Penrith, which constituted 10% of the gardens surveyed.

- Based on its impact on the percentage area distribution of gardens by water saving potential (Figure 6-12)
  - HWaSP gardens: As a result of the reduction in the WaSP achieved through water restrictions for HWaSP gardens, the percentage of the HWaSP garden area has fallen by 56% in Kogarah and by 67% in Penrith. In other words, water saving potential remains to be realized in 44% of the HWaSP gardens.
  - MWaSP gardens: As HWaSP gardens have transformed to MWaSP gardens because of water restrictions, there has been an increase in the percentage area distribution of MWaSP gardens, with Kogarah increasing by 22% and Penrith by 13%.
Effectiveness of water restrictions based on reduction in irrigation application

![Graph showing the impact of water restrictions on irrigation application rate. The graph compares two locations: Kogarah (Top) and Penrith (Bottom). The x-axis represents the annual irrigation applied per unit garden area, while the y-axis represents the number of paired garden sites ordered by irrigation applied before water restrictions. The graph indicates a significant reduction in irrigation application after water restrictions were implemented.]
Effectiveness of water restrictions based on % distribution of water saving potential

Figure 6-11: Impact of water restrictions on percentage area distribution of gardens: Kogarah (Top) vs. Penrith (Bottom)
Effectiveness of water restrictions based on realised water saving potential per house

![Graph showing water saving potential before and after restrictions](image1)

<table>
<thead>
<tr>
<th>Classification</th>
<th>WaSP Levels</th>
<th>Annual Irrigation Rate Exceeds</th>
<th>Annual Landscape Irrigation Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWaSP</td>
<td>High</td>
<td>&gt;250mm</td>
<td></td>
</tr>
<tr>
<td>MWaSP</td>
<td>Moderate</td>
<td>51-250mm</td>
<td></td>
</tr>
<tr>
<td>LWaSP</td>
<td>Low</td>
<td>11-50mm</td>
<td></td>
</tr>
<tr>
<td>NWaSP</td>
<td>None</td>
<td>&lt;10mm</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing water saving potential before and after restrictions](image2)

Figure 6-12: Impact of water restrictions on water saving potential per house: Kogarah (Top) vs. Penrith (Bottom)
6.7 Summary

In this chapter, using a selection of surveyed gardens in Kogarah and Penrith, it was shown how landscape irrigation budget can be used to:

- determine the garden watering characteristics of existing suburban gardens (LWU, MWU or HWU);
- estimate the water saving potential of existing gardens; and
- evaluate the effectiveness of water saving policies such as water restrictions in terms of the water saving potential realised by it.

The application involved data input in the form of historical metered water consumption data for the properties of the domestic garden sites and geo-coded aerial photographs of the properties. The other input required is the benchmark irrigation budgets that were estimated for low water using garden.

Using the geo-coded aerial photos, the gardens were characterised in terms of estimating the landscape area and the percentage breakdown of the landscape area into turf and non-turf zones. Microclimate factors were assigned by noting the orientation of the garden site with respect to the north–south axis in the aerial photographs.

The historical metered water consumption data was used to estimate the volume of water applied externally to the garden. The quarterly irrigation water quantity was estimated by assuming the winter quarter water use to be entirely indoor, and deducting quarterly indoor water use from each of the quarterly water use quantities. It was further assumed that 90% of external water use was applied to the garden to finally estimate the irrigation volume applied in each quarter. Having estimated the quarterly irrigation volume, the irrigation application rate (litres of water applied per square metre of garden area or mm of water applied) for each quarter was estimated by dividing the volumetric irrigation by the landscape area.
The quarterly irrigation rate for MWU and HWU gardens was compared with the irrigation budget for the low water use garden and the difference between the two values noted as the water saving potential (WaSP) of the garden site.

Analysis of the historical metered water consumption data for the period before water restrictions revealed that:

- The irrigation volume applied on the surveyed gardens varied widely in both suburbs, as noted by the high value of standard deviation. The applied irrigation volume did not follow the expected trend of decreasing with decrease in landscape area because of the wide variation in the efficiency of irrigation application. This reinforces the need for an indicator other than annual household water use or applied irrigation volume to differentiate water-efficient garden sites from water-inefficient sites.

- The landscape irrigation budget can be used to compare the irrigation application rate on individual garden sites to determine whether the garden is water efficient or water inefficient, thus proving the utility of landscape irrigation budget as a indicator of water saving potential of domestic gardens at an individual scale as well as collectively.

- The collective water saving potential of the surveyed gardens was determined by noting the percentage area breakdown of the surveyed gardens on the basis of their water saving potential (WaSP) levels, combined with an estimation of average water saving potential per house for gardens belonging in each category of WaSP.

- The effectiveness of water restrictions was also evaluated based on its impact on the irrigation application rate of the surveyed gardens, the average per house annual water saving potential, and percentage area distribution of gardens by their WaSP levels.

Finally, to answer the question that was framed in the beginning of this chapter in the context of Sydney’s water demand, the analyses of the surveyed gardens of Penrith and Kogarah showed that:
Based on the finding that maximum water saving potential of the surveyed gardens was about 50% (49% for Kogarah and 48% for Penrith) of the irrigation demand of the gardens, it can be estimated that the maximum demand management potential for the whole of Sydney is equivalent to 50% of the residential irrigation demand (108 billion litres per year) which equals 54 billion litres per year.

Hence, reaching the 22% reduction in residential irrigation demand achieved by water restrictions (see Section 6.8) leaves scope for further irrigation demand management measures and actions to save the remaining untapped 28% of demand.

Contrary to the belief held by water service providers, water restrictions need to be supplemented by another set of demand management measures and plans such as creating awareness about how plants respond to different soil types with respect to water requirement and facilitating source substitution of reticulated water with rainwater, grey water or stormwater. Increasing the severity of water restrictions is not advisable because it tends to achieve water saving at the cost of losing the quality and associated environmental and social values associated with urban landscapes.

The following conclusions can be drawn based on the estimation of water saving potential of domestic gardens in Kogarah and Penrith:

- WaSP is a better indicator of garden water use and water-use efficiency than annual water use or volumetric irrigation water use.
- In addition to being an indicator of water-use efficiency, WaSP is able to provide an estimate of the volume of water savings that can potentially be obtained from existing gardens and landscapes in urban region.
- Percentage distribution of gardens by their WaSP levels, combined with the estimate of WaSP, can together provide a quantitative estimate of the volume of water savings that can potentially be achieved from gardens in a given suburb with known soil and climate characteristics.
- Water restrictions do not realise all of water saving potential, and therefore there is scope to either supplement or substitute water restrictions with a
policy of irrigation budget allocations for each property to make further savings. The policy of irrigation budget allocation provides community with the opportunity to make their own selection of water saving strategies and thereby offers potential for sustained water savings.
7. Discussion

The aim of this chapter is to discuss the findings of the research as presented in Chapters 5 and 6 within the context of the broader literature in the field of water demand management and urban irrigation. The thesis has specifically contributed to original knowledge to advance the field of water demand management and urban irrigation through:

• The adaptation of *end-use analysis* in the form of the WASP framework to facilitate analysis of urban irrigation demand and estimation of *water saving potential* of urban landscapes.

• The development of a rational method to estimate the minimum irrigation water requirement (*landscape irrigation budget*) to maintain urban landscapes in reasonable health and appearance.

7.1 Adaptation of end-use analysis to analyse urban irrigation demand

Development of a demand management program for any end use relies on the techniques and methods that facilitate analysis of the *existing demand* of the end use in question and comparing the results with the *minimum demand* that can be expected from the end use using the best available technology or best management practice (Gleick et al. 2003). The difference between the two demands provides an estimate of the conservation potential of the end use. End-use analysis at the macro or regional scale has been widely and successfully applied to *existing indoor water demand* (Mitchell et al. 2004; White et al. 2003), and has been successful because it relies on disaggregating indoor demand into its different end uses. With disaggregation it becomes possible to quantify the water conservation potential of individual indoor end uses and rank them in the order of their potential. The approach also allows estimation of the maximum water savings that can be expected if a given end use were to achieve its full water conservation potential. Quantification of water conservation potential provides a greater level of certainty with respect to the return that can be expected from the investment into demand management programs targeting indoor end uses.
To date the end-use analysis approach has not been applied to analysing existing urban irrigation (outdoor) demand (White et al. 2004). Studies on outdoor water use have taken other approaches, such as using probability modelling (Coombes et al. 2000), regression techniques (to correlate indirect factors such as social demographic variables (Troy and Holloway 2004; Syme et al. 2004) and economic factors (Brennan et al. 2007), to existing outdoor (urban irrigation) demand. These approaches do not have the capacity to quantify water saving potential, nor do they help in mapping the location of urban landscapes by their water saving potential. This is why water utilities tend to display more confidence in investing in the development and implementation of indoor demand management programs than in outdoor programs.

What has hindered the application of end-use analysis to outdoor water demand is that, demand being predominantly driven by the requirements of urban landscapes, the analysis needs to incorporate an understanding of the biophysical factors (plant, climates, and soil) that determine demand. To adapt end-use analysis to achieve a satisfactory analysis of urban irrigation demand, it was necessary to integrate it with a biophysical model which could estimate the minimum irrigation water requirement (landscape irrigation budget) for maintaining different urban landscapes in reasonable health and appearance. Integration with a biophysical model was achieved through development of the WASP framework, which is based on the two key concepts associated with urban landscapes, landscape irrigation budget and water saving potential.

The WASP framework consists of two modules. The first is a biophysical module that estimates the landscape irrigation budget for urban landscapes, taking into account the biophysical factors that drive their water demand. The landscape irrigation budget so derived is used in the second module to estimate the water saving potential of the urban landscapes. This end-use analysis is achieved by comparing the landscape irrigation budget with the estimated water actually applied to the urban landscapes, using figures derived from metered consumption data.

The WASP framework proposed in the thesis is based on the principle of disaggregation, which is fundamental to the end-use analysis approach. The application of the WASP framework was demonstrated using a case study of domestic
gardens in the two local government areas of Kogarah and Penrith within the Sydney region, each area representing different soil–climate zones, thus disaggregating the Sydney region into different soil–climate zones. The urban irrigation demand of each zone was further disaggregated into the different urban landscape types that contribute to the overall irrigation demand of the zone, domestic gardens in each area being the landscape types used as the case study for the research. The irrigation demand of the domestic gardens was further disaggregated into two landscape components, turf and shrubs. The only difference between the end-use analysis of indoor demand, and the adaptation of end-use analysis in the form of the WASP framework, is that while the former disaggregates the existing indoor demand, the WASP framework disaggregates the minimum achievable urban irrigation (outdoor) demand. This adaptation is intended to achieve the ultimate objective of the end-use analysis, which is to estimate and quantify the water saving potential of different urban landscape types within each of the soil–climate zones in an urban region and to be able to rank the end uses (urban landscapes) by their water saving potential.

Thus, through development of the proposed WASP framework based on the principles of end-use analysis to enable analysis of urban irrigation demand and the estimation of the water saving potential of urban landscapes, the thesis has addressed a gap that currently exists in the field of water demand management—the lack of a systematic framework for analysing and estimating the water saving potential in the irrigation demand of urban landscapes.

### 7.2 Development of rational method of estimating irrigation water requirement of urban landscapes

Taking account of the biophysical factors that determine the urban irrigation demand lies at the heart of the proposed WASP framework. Accounting for biophysical factors helped the development of a model that can estimate the irrigation water requirement of an urban landscape.

The landscape coefficient, $K_L$, method (Costello et al. 2000) and the modified landscape coefficient method ($K_L + P_{eff}$) (McCabe et al. 2005) were developed for the
The purpose of scheduling irrigation for urban landscapes, large turf areas in particular, in times when water was in relatively abundant supply. These methods are empirical in nature and thus do not take account of the biophysical factors that determine the irrigation water requirement of a particular landscape. While they serve the purpose of scheduling irrigation for turf areas, they are not suitable for estimating domestic landscape irrigation budgets to facilitate demand management.

The \(K_L\) method was developed as an improvement on simple crop evapo-transpiration rates for scheduling irrigation (Costello et al. 2000) by introducing a landscape coefficient that took account not only of evapo-transpiration but also microclimate, planting density and the water use characteristics of the plants making up the landscape. However, the \(K_L\) method does not account for other important biophysical factors such as rainfall, soil characteristics and the root zone depth of the plant types making up the landscape, which influence the irrigation water requirement. The \((K_L + P_{eff})\) method is a modified version of the \(K_L\) method which accounts for the same factors as the \(K_L\) method plus effective rainfall. But, like the \(K_L\) method, the \((K_L + P_{eff})\) method does not account for soil characteristics and the root zone depth of the plants making up the landscape. Thus, both methods are limited for the purpose of determining the landscape irrigation budget that is realistic and can therefore be helpful in facilitating demand management of urban irrigation.

With the intent of developing a rational method that can facilitate urban irrigation demand management, the thesis adapted the \(K_L\) method, which accounts for microclimate, planting density and water use characteristics of plants, and integrated it with a daily water balance model which accounts for evapo-transpiration, rainfall, soil water holding capacity and the root zone depth of the plants.

In Chapter 5, it was shown through a sensitive analysis of individual input model parameters how the proposed WASP framework responds to varying values of input parameters in a way that proves it to be more rational than the existing \(K_L\) and \((K_L + P_{eff})\) methods. It was also shown in that chapter that the \(K_L\) and \((K_L + P_{eff})\) methods produce irrigation budgets which do not discriminate between landscapes located in different soil types—in other words, they produce the same irrigation budgets for landscapes located on different soil types. Both also produce the same irrigation
budgets for shrubs and turf, highlighting their limitations in being unable to discriminate between plant types based on their root zone depth. The rational method used in the WASP framework produces different irrigation budgets responding rationally to variations in soil characteristics as well as plant root zone depth. The landscape irrigation budgets estimated by the rational method are therefore closer to reality than those estimated by currently prevalent methods. Hence WASP provides a starting point to modelling irrigation demand of urban landscapes with the specific view to facilitate demand management of urban irrigation.

The ultimate objective of end-use analysis is estimation of the conservation potential of the end use being analysed. In Chapter 6 it was shown, using as case studies domestic gardens in Kogarah and Penrith, how the WASP framework allows estimation of the water saving potential of domestic gardens by comparing irrigation budgets with the amount of water actually applied to the gardens, estimated from metered consumption data of the properties. It was shown how the WASP framework also helps in classifying domestic gardens on the basis of their level of water saving potential.

Thus, the rational method developed in the thesis to estimate landscape irrigation budget, together with an adaptation of end-use analysis, advances the fields of urban irrigation and water demand management respectively.
8. Conclusion

The thesis set out to answer the following research questions with respect to managing urban irrigation (outdoor) demand.

- How can the end-use analysis approach be applied to analyse urban irrigation demand at a regional scale?
- How can the end-use analysis approach incorporate a rational method of estimating the optimum amount of irrigation water required to maintain a domestic garden within a given soil–climate zone which, when compared to the actual outdoor water use, will help estimate and quantify the water saving potential that exists in urban landscapes.

In answering these questions, the thesis proposed an adaptation of the end-use analysis approach for analysing urban irrigation demand along with introducing and defining the concepts of landscape irrigation budget and water saving potential of an urban landscape. All three elements were integrated into the WASP framework, which consists of Module 1, incorporating a biophysical model for estimation of landscape irrigation budget, and Module 2, incorporating a water demand model for estimation of water saving potential and evaluation of the effectiveness of urban irrigation demand management policies or programs. This necessitated the development of a rational method that can be used for estimating landscape irrigation budget, which was achieved by integrating the landscape coefficient, $K_L$, method (Costello et al. 2000), with a daily soil water balance model.

The thesis then aimed to demonstrate how the WASP framework can be applied to urban landscapes in a given region, using as a case study domestic gardens located in the local government areas of Kogarah and Penrith in the Sydney metropolitan region, representing two different soil–climate zones.

The following conclusions can be drawn from the application of the WASP framework to the domestic gardens, and from the outputs of this application:
Existing methods using the empirical approach (Costello et al. 2000; McCabe 2005) are not suited to supporting demand management and sustainable urban irrigation objectives, as they tend to over-estimate irrigation budgets for three main reasons: a) they do not have the provision to differentiate between soil types and their capacity to store water available to plant roots; b) they do not take account of the deeper root zones of shrubs and other well-established garden plant species; and c) they are based on monthly evapo-transpiration rates less monthly rainfall, not on daily water balance, thus do not take into account short-term water changes to the soil water deficit.

A rational approach to estimating landscape irrigation budgets has the capacity to facilitate and support development and evaluation of demand management measures and policies targeted at urban landscapes, such as domestic gardens. This is because the rational approach produces a realistic estimate of the landscape irrigation budget that responds to the variables which directly influence the landscape water requirement.

The rational approach for estimating the landscape irrigation budget takes account of weather factors (rainfall and evapo-transpiration rate), soil characteristics (water holding capacity), and depth of plant root zone. The approach makes use of the landscape coefficient to scale the reference evapo-transpiration ($ET_0$), using adjustment factors to take account of the water use characteristic of the garden (low, moderate or high water using plant species), the microclimate the garden plants are exposed to (sunny, part sun and part shade, full shade) and planting density. A sensitivity analysis showed that the irrigation budget estimate was most sensitive to the landscape coefficient $K_L$ and the depth of root zone assumed for turf and garden shrubs.

The landscape irrigation budget for the domestic gardens was developed using 100 years of daily rainfall data and reference evapo-transpiration ($ET_0$) to run WASP Module 1 and then, using the 100-year monthly median values of the output of this analysis, to estimate quarterly and annual irrigation budgets. Following is the summary of the results obtained with respect to garden sites in the Kogarah and Penrith local government areas:
• Based on the rational approach, average annual landscape irrigation budget estimates for low, moderate and high water use domestic gardens located in Kogarah were 18% of ET$_O$, 31% of ET$_O$ and 43% of ET$_O$ respectively. Similar gardens in Penrith required estimated landscape irrigation budgets of 12% of ET$_O$, 26% of ET$_O$ and 32% of ET$_O$ respectively.

• The relatively lower irrigation requirement in Penrith, despite the lower rainfall rates and higher ET$_O$ rates that characterise the Penrith climate, were reflective of the greater water holding capacity of the clayey soil that characterises Penrith domestic gardens than the sandy soil that characterises the domestic gardens in Kogarah.

• The calculated irrigation budget estimates have the potential to be used as benchmarks for setting water saving goals and for evaluating the effectiveness of urban irrigation demand management programs and policies.

In evaluating the effectiveness of water restrictions, an analysis of the historical metered water consumption data for the period before and after the enforcement of mandatory ‘water restrictions’, using WASP Module 2, revealed that:

• Before water restrictions were enforced, the surveyed domestic gardens had a total water saving potential equivalent to 50% of irrigation demand. Enforcement of water restrictions achieved an average reduction of 30% in irrigation demand, with untapped water saving potential equivalent to 20% of irrigation demand before water restrictions. Almost 80% of the remaining water saving potential, which is equivalent to a further 16% of irrigation demand, existed in 10% of the surveyed gardens, which had an average water saving potential of 50 kilolitres per household per annum. From this finding it can be concluded that greater water savings can be made in the urban irrigation sector by substituting or supplementing the policy of water restrictions with a policy of allocating landscape irrigation budgets for different urban landscapes commensurate with the soil–climate zone in which they are located.
The thesis has successfully demonstrated how the WASP framework is able to analyse urban irrigation demand to facilitate development and evaluation of urban irrigation demand management policies and programs, through its capacity to:

- estimate landscape irrigation budget
- estimate the water saving potential of urban landscapes
- determine the percentage distribution of properties by their level of water saving potential
- evaluate the effectiveness of programs and policies aimed at reducing the urban irrigation demand.

It was also demonstrated that the WASP framework had the following features:

- The assumptions in Module 1 and Module 2 are transparent to the end user and can be changed by the end user following any new findings.
- It has the capacity to determine water saving goals that can be used not only by water planners and managers at the regional scale but also by individual urban landscape owners and managers at the level of the individual landscape site.
- It uses input data that already exist or that can be obtained with ease.

Because of the above features, WASP has been demonstrated to be simple, transparent, adaptable and flexible, the characteristics that make a decision-making model effective (McNamara 2007).

Limitations of WASP Framework are outlined below along with suggestions for how they may be addressed through further research:

- Since WASP Framework is developed as a first attempt towards developing a rational method for estimation of landscape irrigation budget, it makes use of values of species, density, micro-climate factors published in literature for estimation of landscape coefficient. Hence further research is warranted in refining these values by validating them with landscape outcomes based on
water use, plant, micro-climate and soil data from actual landscapes of different types.

- The WASP Framework relies on making assumptions about the collective water use characteristics of landscapes at regional or macro scale. Application of the WASP Framework would warrant undertaking a survey of a statistically representative number of landscapes being studied in a given soil-climate zone to develop a more robust and refined assumption about the collective water use characteristic of the landscapes.

- The WASP Framework is limited to quantifying the water saving potential of landscapes by location. However, it does not provide insight into the possible reasons for the existence of water saving potential. To develop further insight, further investigation and research would be required in the form of surveying the landscape owners and managers to better understand their knowledge, attitude and skills with respect to irrigation and landscape and their gardening and irrigation practices. In addition, surveying the landscapes with respect to their layout and composition can provide insight with respect to landscapes that are preferred by the landscape owners and managers. Thus, WASP Framework is an effective tool for designing strategic research aimed at developing insight into landscapes and landscape owners with respect to the causes and factors that contribute to water saving and water wasting behaviour in urban irrigation.

- It is also recommended that the framework be piloted and customised with the view to streamline the integration and input of data held by the stakeholder agencies into the framework to make efficient use of existing data in the development of sustainable urban irrigation policy.
9. Bibliography


Appendix 1 – Flyer to Promote Recruitment for Garden Survey

What’s involved?
A visit to your home garden by PhD student conducting the study accompanied by a horticulturist to survey and take notes about your home garden. The visit will last not more than 2 hours.

What’s in it for me & my community?
As a participant, you can find out how much water is ideally needed in your home garden and how you may be able to use less water while still having a great looking garden.

A garden related gift will be given to all participants upon completion of the survey of their garden.

Your participation will also be a valuable contribution to the research that ultimately seeks to benefit the community.

Interested?
To participate or to find out more, contact Ms. Bhakti Devi on Ph (work) 4570 1969 Mobile 0425 392 112 Email Bhakti-Lata.Devi@irrigationfutures.org.au

SAVE
Find out how to use less water, reduce water bills & ease pressure on a limited natural resource.

FREE
Receive a complimentary gift!

EASY
All you have to do is participate in a PhD study to help households achieve a great looking garden with less water, and you’ll reap the benefits too.

Read on to find out how...
Dear Householder,

You are invited to participate in a PhD study that seeks to help home gardeners use less water while maintaining an attractive and healthy garden.

By participating in the study, you will be provided with information about how much water your garden should ideally use for the level of quality that is acceptable to you.

Your participation is important and valuable to the PhD research that ultimately seeks to benefit the community.

Accepting the invitation to participate will involve a visit to your home garden by the PhD researcher (Bhakti) accompanied by a horticulturist.

They will survey your garden and take notes about its design etc. Their visit will last for a maximum of two hours.

Upon completion of the survey, you will be given a garden-related gift in appreciation for your participation in the study.

The survey is scheduled to be conducted this spring (Sept or Oct/Nov 2006). The survey date will be pre-arranged in consultation with interested participants.

To accept the invitation or to make an enquiry please call Bhakti on 4570 1969 (her work) or 0425 392 112 (her mobile).

Across Sydney, the water we use outside our homes each day would fill 250 Olympic swimming pools! This is equivalent to 25% of Sydney’s total household water consumption. The garden is a great place to start when looking at ways to save water and reduce our water bills.
## Appendix 2 – Survey Data Sheet

<table>
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<tr>
<th>Property ID #</th>
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<tbody>
<tr>
<td>Property Address</td>
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<td>Property Size</td>
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<tr>
<td>Property Age</td>
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<td>Property Value</td>
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<td>$300K-500K</td>
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<td>Who designed the garden?</td>
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<tr>
<td>Acceptable level of landscape outcomes?</td>
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<tr>
<td>Lush Green/ Moderately Green/ Low Maintenance/ Don’t care</td>
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<tr>
<td>Watering method used (When no restrictions)</td>
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<tr>
<td>Watering frequency (when no restrictions)</td>
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<tr>
<td>Summer:</td>
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<td>Winter:</td>
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<td>Soil Type:</td>
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<td>Times of exposure to sun</td>
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<td>Front yard:</td>
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<td>Back yard:</td>
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<tr>
<td>Mulching</td>
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<td>Extent</td>
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<tr>
<td>Material used:</td>
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<tr>
<td>Species Identification: FRONT YARD</td>
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<td><strong>Tree Species</strong></td>
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<td><strong>Shrub Species</strong></td>
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<td><strong>Ground Cover Species</strong></td>
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<td><strong>Pot Plants</strong></td>
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<tr>
<td><strong>Vegetables</strong></td>
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<td>Species Identification BACK YARD</td>
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<td>Tree Species</td>
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<td>Ground Cover Species</td>
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<td>Pot Plants</td>
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