remote sensing

MDPI

Comparing Three Approaches of Evapotranspiration Estimation in Mixed Urban Vegetation: Field-Based, Remote Sensing-Based and Observational-Based Methods

Hamideh Nouri [1,*], Edward P. Glenn [2], Simon Beecham [1], Sattar Chavoshi Boroujeni [1,3], Paul Sutton [1], Sina Alaghmand [1,4], Behnaz Noori [5] and Pamela Nagler [6]

[1] School of Natural and Built Environments, University of South Australia, Adelaide, SA 5095, Australia; Simon.Beecham@unisa.edu.au (S.B.); sattar.chavoshi@unisa.edu.au (S.C.B.); Paul.sutton@unisa.edu.au (P.S.); sina.alaghmand@monash.edu (S.A.)

[2] Department of Soil, Water and Environmental Science, University of Arizona, Tucson, AZ 85726, USA; EGlenn@ag.arizona.edu

[3] Soil Conservation and Watershed Management Research Institute of Iran, Tehran 1136-13445, Iran

[4] Discipline of Civil Engineering, School of Engineering, Monash University Malaysia, Selangor 47500, Malaysia

[5] College of Agriculture and Natural Resources, University of Tehran, Tehran 31587-77871, Iran; beh_nouri@ut.ac.ir

[6] US Geological Survey, Southwest Biological Science Center, Tucson, AZ 85721, USA; pnagler@usgs.gov

* Correspondence: Hamideh.Nouri@unisa.edu.au; Tel.: +61-883-023-313

Abstract: Despite being the driest inhabited continent, Australia has one of the highest per capita water consumptions in the world. In addition, instead of having fit-for-purpose water supplies (using different qualities of water for different applications), highly treated drinking water is used for nearly all of Australia's urban water supply needs, including landscape irrigation. The water requirement of urban landscapes, particularly urban parklands, is of growing concern. The estimation of evapotranspiration (ET) and subsequently plant water requirements in urban vegetation needs to consider the heterogeneity of plants, soils, water, and climate characteristics. This research contributes to a broader effort to establish sustainable irrigation practices within the Adelaide Parklands in Adelaide, South Australia. In this paper, two practical ET estimation approaches are compared to a detailed Soil Water Balance (SWB) analysis over a one year period. One approach is the Water Use Classification of Landscape Plants (WUCOLS) method, which is based on expert opinion on the water needs of different classes of landscape plants. The other is a remote sensing approach based on the Enhanced Vegetation Index (EVI) from Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on the Terra satellite. Both methods require knowledge of reference ET calculated from meteorological data. The SWB determined that plants consumed 1084 mm· yr^{-1} of water in ET with an additional 16% lost to drainage past the root zone, an amount sufficient to keep salts from accumulating in the root zone. ET by MODIS EVI was 1088 mm· yr^{-1}, very close to the SWB estimate, while WUCOLS estimated the total water requirement at only 802 mm· yr^{-1}, 26% lower than the SWB estimate and 37% lower than the amount actually added including the drainage fraction. Individual monthly ET by MODIS was not accurate, but these errors were cancelled out to give good agreement on an annual time step. We conclude that the MODIS EVI method can provide accurate estimates of urban water requirements in mixed landscapes large enough to be sampled by MODIS imagery with 250-m resolution such as parklands and golf courses.

Keywords: evapotranspiration; urban irrigation; drainage; lysimeter; Neutron Moisture Meter (NMM); soil water balance

1. Introduction

1.1. Need for Evapotranspiration (ET) Estimates for Urban Landscapes

The UN Population Reference Bureau [1] states that 51% of the world population is settled in urban areas and that this ratio will reach 60% by 2030 [2]. Rapid urban population growth necessitates sustainable urbanisation planning and management. To avoid severe environmental consequences and climate change impacts, green urbanisation needs to be facilitated [3]. Preserving and even expanding urban green spaces is one of the principles of green urbanisation. Despite this, the water management of urban green spaces such as inner-city parklands compared with natural vegetation and agricultural areas has received much less attention [4]. In addition, the increasing application of wastewater irrigation in urban green spaces also highlights the need for sustainable irrigation management of urban vegetation [5–7].

Water demand and subsequent evapotranspiration (ET) through vegetation is a fundamental concept of sustainable irrigation [8]. "The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration" [9]. In many agricultural systems, there is a uniformity of density, height, and water availability which facilitates a conventional approach for ET measurement, although these approaches are not without their challenges. In the case of non-agricultural systems, such as inner-city gardens and urban parks, the heterogeneous nature of vegetation and landscapes, together with the high spatial and temporal variability of soil and water characteristics, and the variability of management and watering practices [10] contribute to greatly increased complexity in the ET estimation of urban vegetation [11,12]. This is of even more concern when wastewater irrigation is occurring due to the risk of nutrient leaching that, in the long term, can result in soil and groundwater contamination [10,13].

In this study, we compared two practical methods for ET estimation in Veale Gardens, an urban park in Adelaide, Australia with a detailed estimation of ET based on a soil water balance (SWB) approach. One method was the Water Use Classification of Landscape Species (WUCOLS), an observation-based program calibrated for the type of landscape plants and local climate at the study site. The second method was based on satellite imagery combined with meteorological data. Our goal was to find a reliable yet convenient method for estimating actual water requirements of urban landscapes in a hot Mediterranean climate.

1.2. Soil Water Balance

For almost a century, ET has been determined through monitoring of temporal changes in soil moisture status. Soil sampling and gravimetric analysis are primary techniques of soil moisture measurement. These techniques have been gradually improved through the application of electromagnetic devices such as capacitance-based time domain reflectometry (TDR) and neutron thermalization methods. The SWB technique is one of the conventional methods of ET estimation that has benefitted from the application of these electromagnetic devices in soil water monitoring. SWB is an account of all volumes of water added, removed, or stored over a given time interval [14]. Precipitation or irrigation that reaches the soil surface may infiltrate or run off. The infiltrated water may evaporate from the soil or be captured by vegetation where it is either used by plants for growth, transpired from stomata, or drained from the effective root zone [15]. Monitoring all these inflows and outflows is the fundamental principle of the SWB method.

The SWB method has - sources of error and inaccuracy, particularly when applied in large areas. Finding representative sample points that perfectly characterize soil water properties, such as drainage, soil bulk density, water holding capacity, and saturated hydraulic conductivity, is challenging. This is of more concern in urban landscape plantings due to the heterogeneity of vegetation, soil, water, and urban microclimates. Testi *et al.* [16] compared the SWB and eddy covariance methods in an orchard. They recommended that ET estimation of young orchards should be a mechanistic approach

that deals with evaporation from soil and plants separately. Kizito *et al.* [17] confirmed the suitability of the application of the SWB for native shrubs. Scott [18] compared the eddy covariance and SWB methods in a watershed covering shrub land, grass land, and savannah sites. The results from the two methods showed a better agreement in drier years. Trambouze *et al.* [19] compared ET estimation of a row-cropped vineyard using the SWB and energy balance methods. They reported that the SWB must be used over a period longer than one week (preferably a year or more) to provide acceptable ET estimation. While the SWB approach can provide accurate data, it is not practical to apply it to routine, near-real-time monitoring of landscape ET, as is needed for irrigation scheduling.

1.3. The WUCOLS Method

Nouri *et al.* [20] compared three observational-based methods of ET estimation in urban landscape vegetation. Three adjustment factors, or landscape plant coefficients, for reference ET (ET_o), namely WUCOLS, plant factor (PF), and a crop stress factor for the Irrigated Public Open Space (IPOS_2008) method, were estimated. The predicted irrigation rates using these three landscape factors were compared with actual irrigation rates for Veale Gardens, the site of the present study.

In the IPOS-2008 method, the landscape factor is the product of a plant factor and plant stress factor that varies from 0.4 for passive recreational turf to 1.0 for elite sport turf. This method is mainly focused on turf grasses. In this approach, plant evapotranspiration (ET_L) is calculated by relating ET_o to a turf grass coefficient (K_c) and a crop stress factor (K_{st}).

$$ET_L \ = \ ET_o \times K_c \times K_{st} \qquad\qquad (1)$$

The Plant Water Use Factor (PF), which defines a landscape coefficient for the minimum irrigation needed to maintain acceptable function aesthetics aspects, was also tested. This method was very limited in species and did not cover a majority of species in the study area.

$$ET_L \ = \ ET_o \times PF \qquad\qquad (2)$$

The results confirmed that the WUCOLS method produced the best estimation of urban vegetation water requirements for the study area, so it was adopted for the present study. WUCOLS is based on the expert opinion of a panel of 36 landscape horticulturists regarding water requirements for different classes of landscape plants, and it is calibrated for local conditions using estimates of reference ET (ET_o), plant types and species, vegetation density, and microclimate factors:

$$ET \ = \ K_L \times ET_o \qquad\qquad (3)$$

where K_L is a coefficient similar to the crop-coefficient used for agricultural crops, but incorporating factors specific for urban landscaping plants. ET_o is based on meteorological data and represents the maximum ET expected for a well-watered grass crop [9]. The WUCOLS method is practical because it does not require actual local measurements of ET. However, it is qualitative in the sense that it depends on expert opinion rather than measured properties of the landscape, and it is difficult to extend to landscapes beyond those for which it was developed and validated.

1.4. Remote Sensing Method

Satellite imagery has been used to estimate ET in agricultural and natural ecosystems for the past 25 years [21]. Vegetation index methods, as applied in this study, use optical bands to estimate canopy greenness, which is directly related to the transpiration component of ET. These methods are appropriate for monitoring urban landscapes where maintaining healthy green vegetation is the ultimate goal [11,12]. Nouri *et al.* [22] showed that ET could be predicted at the study site using high-resolution WorldView 2 imagery by creating masks denoting individual classes of plants. However, WorldView 2 images are expensive, and digitizing individual landscape units is tedious.

A much simpler remote sensing method using Moderate Resolution Imaging Spectrometer (MODIS) sensors on the Terra satellite was also tested by Nouri *et al.* [22] and yielded promising results, but actual ET rates were not available for comparison with any of the methods.

1.5. The Present Study

This study compared SWB, WUCOLS, and MODIS methods for estimating ET at Veale Gardens. The SWB method was accepted as the most accurate reference estimate of ET since it measured all input and outputs; the two practical methods were compared to SWB estimates to determine the best method for routine monitoring of ET for parks and other urban landscapes that have mixed vegetation types.

2. Materials and Methods

2.1. Site Description

Field monitoring was undertaken from November 2011 to November 2012 at Veale Gardens (VG), which is part of Park 21 within the Adelaide Parklands. The Adelaide Parklands includes a total of 29 parks that form a green belt of approximately 7.6 km^2 encircling the city centre of Adelaide. VG is fully covered by kikuyu turf grasses and also contains more than 60 species of trees and shrubs that are irrigated using recycled wastewater (EC < 2 dS/m) [13]. Thirty years of meteorological records for Adelaide (1981–2010) collected at the Kent Town station located 2.9 km from the study site show that Adelaide experiences mostly warm summers (December–February) and fairly cold winters (June–August). The long-term average annual precipitation is approximately 549.1 mm, which falls on average over 128 rainy days in a year [23]. Soil samples from four bores in VG show a texture of silty loam with a pH range of 8.0 to 8.8 and electrical conductivity (EC) less than 2 dS/m.

An EC soil map was plotted using electromagnetic soil mapping (EM38) as a preliminary soil survey in VG. Based on the soil EC map, four sampling points—L1, L2, L3, and L4—in the low EC zone (EC ⩽ 1.2 dS/m) were established (Figure 1). Boreholes were drilled to a depth of 4 m at each of these four positions.

(a)

(b)

Figure 1. (**a**): instrument array for determining the soil/water balance in Veale Gardens (34,569.9140 S, 1,383,549.4899 E); (**b**): Lundie Garden, Veale Gardens, and Kurrangga Park, with red squares showing an approximate center of 250 m × 259 m. Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index pixels obtained to determine evapotranspiration.2.2. Experimental Design.

2.1.1. Soil Water Balance Components

The SWB equation uses conservation of mass principles in a closed system to describe the water flow in and out of a hydrological domain [24,25]. Plant water requirements are supplied through soil water storage (ΔS), which is the residual of input and output water to the soil (Equation (4)).

$$P + I + W - ET - R - D = \pm [\Delta S].\qquad(4)$$

The input and output components are precipitation (P), irrigation (I), upward contribution from water table (W), surface runoff (R), and drainage (D) [26–28]. To estimate the *in-situ* ET of mixed vegetation in VG, the differences between the total amounts of input water (irrigation and precipitation) and the amounts of output water (soil moisture changes, drainage, and runoff) were measured.

2.1.2. Precipitation and Irrigation Data

Precipitation data during the experiment were collected by an automated wireless weather station located in VG less than 200 m away from the sampling points. An automatic sprinkler irrigation system was used in VG. Irrigation data was provided by Adelaide City Council (ACC) for the study period. Three different pop-up sprinkler types (Hunter I-31, Hunter I-20 ultra, and Hunter institutional) were used. The irrigation rates of the sprinklers varied from 11.9 mm/h to 23.8 mm/h depending on the pressure and effective radius. ACC, who manage the Adelaide Parklands, reported an irrigation efficiency (uniformity of application) of 70% for the entire park (ACC, personal communication).

2.1.3. Soil Moisture Content Measurement Using Neutron Probes

The moisture status in the soil profile was monitored using a Neutron Moisture Meter (NMM), which is a method that has been broadly employed to quantify soil water content in research and commercial applications [29–32]. NMMs contain a radioactive source that emits fast neutrons and a detector of slow neutrons. Both the source and the detector are placed in a probe. Soil protons (commonly soil water) and fast neutron interactions slow down by collision with hydrogen in the soil water molecules, and the returned signal is captured and quantified by the NMM probe. In VG, electro-galvanized access tubes with internal diameters of 50 mm were installed at the four sample points of L1, L2, L3, and L4 (Figure 1). These four points were selected from different vegetation densities and species status. The tubes were capped on top to prevent entry of any soil, water, or animals. The NMM readings were taken monthly at 0.2-m depth intervals down to 1 m and then at 0.5-m intervals down to 4 m.

Considering the inherent heterogeneity of soil and water conditions from site to site, an *in-situ* NMM calibration was conducted [29,31]. The NMM calibration exercise and all the subsequent NMM readings utilized a CPN503 DR Hydro-probe and 32 s count rates. A standard count was undertaken by taking a NMM reading of a suspended access tube in the middle of a water drum. A field calibration was conducted by taking NMM readings at the same interval in the monitoring tubes down to 4 m. The guideline by Goyne and Williams [31] was employed to follow a step-by-step procedure of installing, setting up, calibrating, reading, and processing the data of NMM. Yao *et al.* [33] employed a similar approach of calibration. Destructive soil sampling down to a 4 m depth next to the access tube (20 cm) enabled measurement of the gravimetric soil moisture content for each interval corresponding to the NMM reading locations. This procedure was repeated for two soil moisture conditions representing the upper and lower limits of soil moisture in VG (total of 20 data points). Statistical analysis of the NMM records in the upper limit (soil saturation condition) and the lower limit (soil dry condition) produced a calibration curve relating soil volumetric moisture to count ratio and confirmed a calibration equation that was developed for VG:

$$\text{Soil Moisture } (\text{cm}^3 \cdot \text{cm}^{-3}) = 80.9\text{CR} - 30.0, \text{r}^2 = 0.83, p < 0.001 \, \text{CV} = 11.2\%\qquad(5)$$

2.1.4. Drainage Measurement Using Lysimeters

Two zero-tension pan lysimeters were installed in VG to measure the drainage during the period November 2011 to November 2012. Based on the landscape variation in the park, two landscape zones were defined, one being largely covered with turf grasses containing a few trees and shrubs and the second zone consisting mostly trees and shrubs with intermittent turf grasses. Lysimeters were placed horizontally and 100 cm below the ground to capture water draining from the above lying undisturbed soil. The lysimeter in landscape zone 1 was located below turf grasses with the closest tree 15 m away. The lysimeter in landscape zone 2 was buried close to a tree with effective root zone of one meter. The installation method for the pan lysimeters is described in detail by Nouri *et al.* [13].

2.1.5. Monitoring of Water Table Heights and Surface Runoff

Since the commissioning in 2010 of the recycled wastewater irrigation scheme used in the Adelaide Parklands, groundwater levels have been measured at least every three months using a calibrated water level probe to take into account the upward contribution from the water table (W) in the SWB equation. Surface runoff is mainly generated by the two mechanisms of saturation excess runoff and infiltration excess runoff [34].

Previous studies showed that surface runoff was not a factor in the water balance [35]. Pirone *et al.* [36] stated that runoff can be neglected in the SWB approach in dry seasons. Moreover, we did not observe any surface runoff during the study period.

2.2. Water Use Classification of Landscape Plants (WUCOLS)

The water demand of urban vegetation is directly related to the amount of water that is lost through the landscape evapotranspiration process, which is fulfilled by effective precipitation (P_E) and net irrigation (I_N):

$$I_N = ET - P_E \tag{6}$$

Net irrigation is the required water to satisfy vegetation evapotranspiration excluding effective rainfall. The heterogeneity of mixed vegetation in urban environments provides a situation that cannot be readily replicated by conventional crop coefficient methods. WUCOLS was developed by Costello and Jones [37] as a more practical approach for estimating ET from urban landscape plantings. WUCOLS introduces an adjustment factor to ET_o in order to estimate the ET of urban landscape plantings, as expressed in Equation (3).

K_L takes into account a species factor (K_s) that accounts for differences in vegetation species, a density factor (K_d) that accounts for the variation of canopy cover/vegetation density, and a microclimate factor (K_{mc}) that accounts for the effects of typical urban features such as buildings, paving, and shading (Equation (7)).

$$K_L = K_s \times K_d \times K_{mc}. \tag{7}$$

A comprehensive description of assigning species, density, and microclimate factors for VG is reported by Nouri *et al.* [20]. It should be noted that VG is operated by the Adelaide City Council, irrigating by an adequate resource of the recycled wastewater. Therefore, soil moisture stress is not included, and plants are assumed to not be water-stressed.

2.3. MODIS ET Method

MODIS images are obtained at a near-daily rate for most areas of the Earth. MODIS MOD 13-gridded 250-m-resolution vegetation index products are supplied to end-users by NASA as atmospherically and radiometrically corrected 16-day composite images (for details of image acquisition and processing see [38]. MODIS Enhanced Vegetation Index (EVI) images for the years 2000 to 2013 were obtained from the Oak Ridge National Laboratory DAAC site (Oak Ridge National

Laboratory, 2014). The pixel selection tool at the website displays the approximate MODIS pixel footprint on a high-resolution Google Earth image; hence, it is possible to positively co-locate ground sites with pixel acquisition sites if images or maps are available for the ground site locations. A single EVI pixel wholly contained within the Veale Gardens was obtained for this study. Pixels for two adjacent parks, Lundie Garden and Kurranga Park, where obtained for comparison. The choice of EVI as the VI product was based on its superior performance in predicting ET, as noted in previous studies [39]. EVI is calculated from band reflectance values as:

$$EVI = 2.5 \times (NIR - Red)/(1 + NIR + (6 \times Red - 7.5 \times Blue)) \tag{8}$$

where the blue and red coefficients, 6 and 7.5, minimize residual aerosol variations [40,41].

ET has been accurately estimated by combining MODIS EVI with knowledge of atmospheric water demand, as estimated by at a number of agricultural and riparian phreatophyte communities in diverse locations [42,43]. We used an algorithm derived from the crop-coefficient method of estimating ET of agricultural crops, where:

$$ET = K_c \times ET_o \tag{9}$$

where ET_o is reference (potential) ET calculated from meteorological data, and K_c is an empirical coefficient relating ET of a particular crop to ET_o, typically on a monthly basis through the crop growth cycle [9]. A satellite VI can replace K_c in Equation (3), giving an estimate of ET based on a measure of the actual status of the crop at the time of satellite overpass (reviewed for different natural and agricultural ecosystems by Glenn *et al.,* 2010):

$$ET = fVI \times ET_o \tag{10}$$

where *f*VI is a function describing the relationship between the VI and ET, determined by regression of VI with the measured values of ET and ET_o, as from moisture Bowen Ration flux towers, lysimeters, or water balance studies. The relationship between ET and VI is not necessarily linear because VIs are typically non-linear with respect to Leaf Area Index (LAI). The algorithm we used was [43]:

$$ET = ET_o \times 1.65 \left(1 - e^{-2.25EVI}\right) - 0.169 \tag{11}$$

The term $(1 - e^{-2.25EVI})$ takes the form of the Beers–Lambert Law as applied to light absorption by a canopy, with $-2.25 \times EVI$ replacing LAI. The numerical coefficients were derived from the equation of best fit between ground-based ET from literature data for four irrigation districts and four riparian forest in arid and semiarid districts in Spain, Australia, and the Western U.S. The algorithm reproduced annual ground estimates of ET with an average error of 5.5%, ranging from 2.9%–9.3% across sites and with an overall bias of −5.3% across sites [43]. We applied this algorithm to the Veale Gardens site in this study. A previous study in VG [22] showed a significant positive correlation between the field-based approach of WUCOLS and remote sensing-based approach using high-resolution WorldView 2. This strong relationship validated a remotely sensed ET estimation approach. Further analysis using coarse resolution MODIS imageries strongly supported the feasibility of vegetation indices to estimate ET rate of heterogeneous urban vegetation.

3. Results

3.1. SWB Components

Total amount of input water and output water are reported in Table 1. The total precipitation from December 2011 to November 2012 was 555.2 mm, which is very close to the long-term average rainfall in Adelaide (549.1 mm). As expected, the highest rates of precipitation were in the wet winter months, while the lowest precipitation rates occurred in summer. The total irrigation applied during the study period was 720.48 mm (ACC, personal communication). From No supplemental irrigation

water was required during winter and early spring, while maximum irrigation rates were applied in summer (Table 1).

Table 1. SWB components and ET estimates in Veale Gardens, 2011–2012. Soil moisture is in mm of water in the top 4 m of the soil profile.

Month	Precipitation (mm)	Irrigation (mm)	Drainage (mm)	Soil Moisture (mm)	ET SWB (mm)	ET WUCOLS (mm)	ET MODIS (mm)
11 December	22.0	119.28	0.34	1050.8	183	114	125
12 January	26.6	145.08	0.08	1087.13	135	125	150
12 Feburary	18.0	159.92	0.08	1118.274	147	81	96
12 March	34.2	90.68	0.28	1131.22	112	79	105
12 April	70.2	49.28	3.51	1139.25	108	51	68
12 May	28.8	46.36	8.58	1138.13	68	30	42
12 June	61.0	0	37.25	1142.31	20	24	31
12 July	130.5	0	67.08	1175.27	30	26	42
12 Augest	67.8	0	11.17	1138.68	93	36	59
12 September	64.4	0	35.42	1138.46	29	64	110
12 October	17.8	44.56	12.33	1141.12	47	76	106
12 November	18.9	65.32	0.02	1113.8	112	96	154
Total	560	720	176	-	1084	802	1088

There were significant differences in monthly values that cancelled out to give a good agreement on an annual scale. Having a small range of values in soil moisture, CV was about 11.2%.

To complete the SWB data requirements, estimates of runoff, groundwater changes, and soil moisture storage changes were needed. The depth to groundwater is approximately 4 m below the ground surface, as reported by Martin *et al.* [35]. Consequently, there is no input contribution from the water table height in the SWB equation. To minimize the risk of excess runoff, an existing automated irrigation system was used in VG, and this was managed using real-time meteorological data together with soil moisture probe monitoring. Accordingly, there were no runoff losses measured during the study period. Changes in soil moisture in the top 4 m of the soil profile were factored into the SWB calculation, but the soil was always moist, and changes were small over the one-year study period, with soil moisture ranging only from 1051–1175 mm (equal to 0.262–0.293 $cm^3 \cdot cm^{-3}$). While no runoff was observed in previous studies, we did not directly measure runoff. This might introduce a possible source of error to the water balance method [11]. However, the soil remained below saturation, even following rains.

The following figure (Figure 2) shows the dynamics of the soil water change during the study period. ET in VG was mainly affected by the characters of the vegetation and the weather factors rather than soil moisture status.
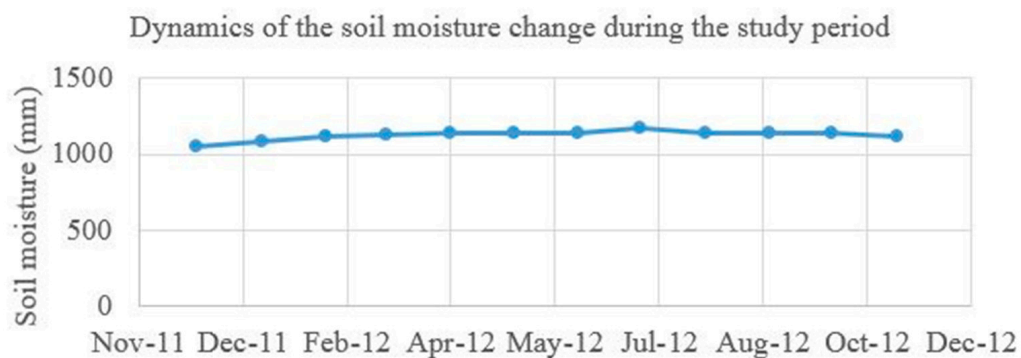

Figure 2. Soil moisture status during the study period.

The total annual ET for the year estimated by SWB was 1084 mm. Total water in was 1283 mm, of which precipitation contributed 560 mm (44%), and irrigation 723 mm (56%). Drainage past the root zone was 176 mm. This amounts to a leaching fraction of 0.16. An additional 23 mm was retained in the vadose zone.

3.2. WUCOLS ET Estimate

A list of the most common tree and shrub species in VG was compiled. Based on the regional classification by Costello *et al.* [44], a species factor of 0.53 was assigned for VG according to the moderate water requirement of the species. This value was selected following a survey by a panel of six horticulturists who work for ACC. This panel classified the variety of plant species in VG into three categories, drought tolerance, moderate tolerance to drought, and drought sensitivity, in order to maintain acceptable health and appearance. The panel similarly assigned an aggregated moderate water requirement class for VG. Since the experimental site is fully covered by turf grasses with few trees and shrubs, a density factor of 1 was assigned. Considering the effects of urban features such as buildings and parking lots, a microclimate factor of 1.05 was assigned for VG. This resulted in an overall landscape coefficient for the experimental site of 0.56 as a product of the species, density, and microclimate factors.

The total estimate of water requirement by WUCOLS was 802 mm, 26% lower than the SWB ET estimate and 37% lower than the water actually applied including the leaching fraction (Table 1). Hence, the WUCOLS estimates could be an under-representation of actual water requirements at Veale Gardens.

3.3. MODIS Estimate and Comparison of Methods

EVI was negatively correlated with ET_o in Veale Gardens ($r^2 = -0.57$, $p = 0.005$). The garden was evergreen and tended to be greenest during the winter months, perhaps due to heat stress in the summer (Figure 3). Total ET by MODIS was 1088 mm, very close to the SWB estimate (Table 1).
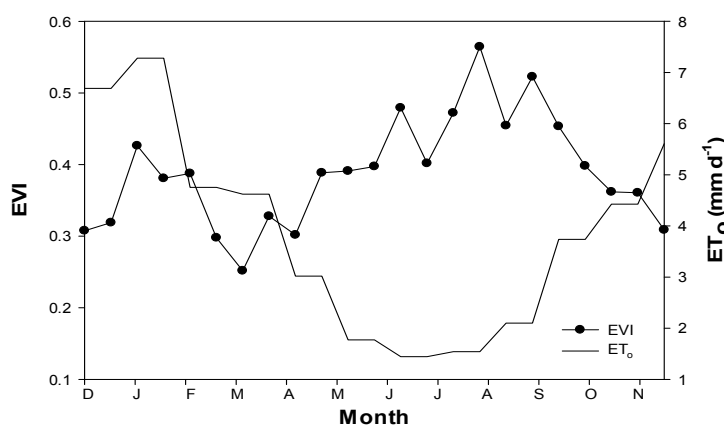

Figure 3. MODIS Enhanced Vegetation Index and potential evapotranspiration (ET) for Veale Gardens, December 2011 to November 2012.

Both the MODIS and WUCOLS adequately captured the seasonality of ET at Veale Gardens, with highest values in December (Australian summer) and lowest in June (Australian winter) (Figure 4). The SWB estimates were more variable month to month than the WUCOLS and MODIS estimates.

There was no variance available for the MODIS estimate since it was based on a single pixel, but the standard deviation for the SWB method was 52.03.

The MODIS method adequately predicted annual ET as measured by a detailed SWB approach. To further test the method, ET values for Veale Gardens and two adjacent parks were calculated for the 2001–2013 period (Figure 5). Veale Gardens had higher ET than the two adjacent parks

due to the presence of more trees in VG compared to the other two parks. However, all three had regular annual cycles of ET with no downward trend over the years, indicating overall appropriate management practices.
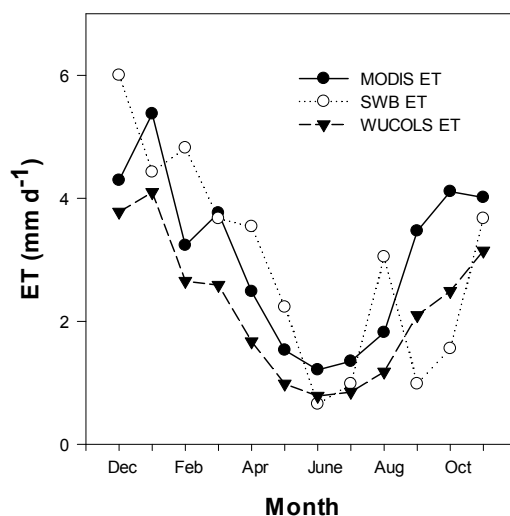

Figure 4. ET at Veale Gardens from December 2011 to November 2012 estimated by MODIS, soil water balance (SWB) and Water Use Classification of Landscape Plants (WUCOLS) methods.
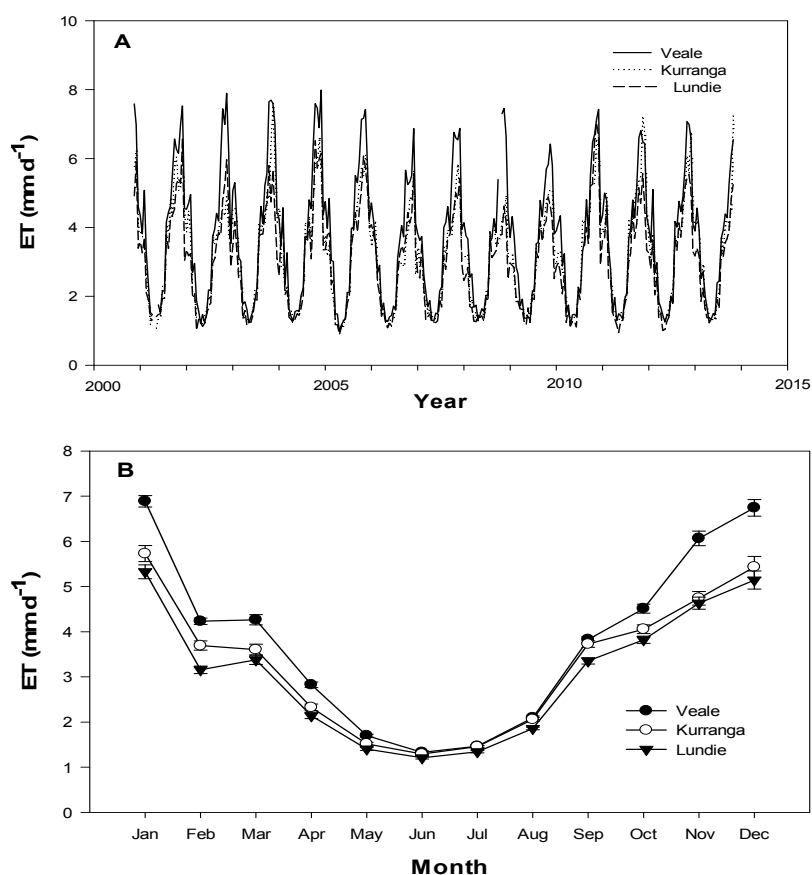

Figure 5. (**A**) ET estimated by MODIS EVI at 16-day intervals, 2000 to 2013, for three adjacent park areas in Adelaide, Australia; (**B**) Monthly ET values averaged over all years for the same sites. Error bars are standard errors over years.

4. Discussion

The SWB shows that water management at Veale Gardens efficiently maintains the plants without over-irrigating the landscaping [13,20]. The observed leaching fraction of 0.16 is a reasonable value to keep soil salinity within the range tolerated by the mixed plantings [45].

In summary, two ET estimation approaches of observational-based WUCOLS and the remote sensing-based approach of EVI from MODIS imagery combined with ET_o were applied in the heterogeneous urban vegetation of the VG within the Adelaide Parklands over a year. These approaches were compared with the field-based approach of SWB. The SWB determination of annual water demand was 1084 mm with an additional 16% drainage loss. Annual ET by EVI from MODIS was 1088 mm, 0.3% more than SWB estimate. The total annual water requirement estimated by WUCOLS was only 802 mm, 26% lower than the SWB and 37% lower than actual irrigation rate, including the drainage fraction. In the SWB, the range of soil moisture was small (CV = 11.2%) indicating urban vegetation in VG was not water-stressed during the study period. In other words, our outcomes were mainly affected by vegetation status and meteorological influences rather than soil moisture availability. It should be noted that the individual monthly ET by EVI-MODIS was not accurate, but these errors were cancelled out to give good agreement on an annual time step. Our results show that the EVI-MODIS method can provide an accurate estimation of annual ET in urban heterogeneous urban landscapes. However, the area needs to be large enough to be sampled by 250-m spatial resolution by MODIS imagery. Nouri *et al*. [22] found NDVI from high-resolution WorldView 2 imager to be a reliable and effective approach for the ET estimation of mixed urban vegetation. Kumar [46] analyzed RS-based VIs to improve the water resource management of urban environments. He found VIs valuable indicators for studying soil moisture and ET.

Sustainable irrigation and water management necessitates a precise knowledge of ET, particularly in a mixed vegetation environment. This study investigated the important challenges of determining a reliable and practical approach to measuring the water demand of heterogeneous urban vegetation, which is not widely available in the irrigation literature. A conventional approach for measuring plant water requirements is used in many agricultural systems, as there is a uniformity of crop species and height. However, this approach is still not without its challenges. Estimating ET and subsequently plant water requirements in non-agricultural systems such as urban parks, forests, and riparian systems is made more complex due to the wide variation in vegetation types involved, including trees, shrubs, and grasses, with different species, vigour/stress, density, height, microclimate, and water demand/availability.

Allen *et al*. [47] assessed the accuracy of different methods for estimating ET and irrigation requirements. Methods included lysimeters, eddy covariance and Bowen ratio flux towers, soil water balance, and satellite-based remote sensing, among others. All methods were subject to errors and uncertainties, which translated into economic losses due to misinformed water management. Lysimeter and soil water balance methods had the highest accuracy, with annual errors of 5% and 10%, respectively. Hence, the good agreement between the SWB method and the MODIS results in the present study are encouraging. However, based on literature results, remote sensing methods had a range of accuracy of 5% to 30% depending on method and type of ecosystem. In a previous study, the MODIS method used here produced results within 5% of the eddy covariance flux tower results on an annual basis [43], similar to the agreement with the SWB results in this study.

However, we do not recommend SWB as a practical approach to studying ET of large-scale urban parklands, as it is costly and needs extensive time, high-level technicians skilled in building and installing drainage compartments, and someone with a radiation license to work with Neutron Moisture Meter probes. The high spatiotemporal variation of heterogeneous mixed landscape vegetation areas introduces sources of errors and biases in representative sample points in measuring water balance factors such as drainage and soil moisture. Moreover, there are always some restrictions when undertaking fieldwork in public parks that limit the number of sampling points and the duration of the study. This research team has investigated the possible capability of remotely sensed vegetation

indices, such as NDVI from WorldView 2 and EVI from MODIS, to estimate the ET of heterogeneous urban vegetation in VG. We found high-resolution NDVI to be a precise and valid indicator in seasonal ET estimation. However, due to the high cost associated with high resolution imagery, we examined MODIS EVI as an alternative. Our results showed that the MODIS EVI method works very well for annual ET estimation in urban parklands. This finding supports findings of other remotely sensed vegetation indices as a feasible ET estimator in unstressed conditions [9,48]. For example, Maselli *et al.* [49] discuss relevant limitations of ET estimation in mixed, water-stressed ecosystems such as forests and reported a satisfactory accuracy in using vegetation indices from MODIS. Wang *et al.* [50] studied the water balance cycle over Australia. They found satellite products including ET from MODIS to be a suitable estimate in large time scales of seasonal or annual balance.

5. Conclusions

It would be impractical to conduct detailed SWB studies in all the parklands in Adelaide as an irrigation management tool. MODIS imagery combined with ET_o accurately reproduced annual ET as determined by the SWB, while WUCOLS underestimated both ET and total water requirements. The K_L coefficient in WUCOLS could be adjusted (increased) to force agreement with the SWB, but this would be a static estimate of water requirements. On the other hand, water application rates, and subsequently their impact on EVI and ET tested by the MODIS method, could be adjusted to fine tune irrigation practices.

MODIS vegetation index imagery is currently available as pre-processed, atmospherically corrected products at no cost; hence, it is a practical method for estimating urban plant water requirements. Replacement satellites for Terra and Aqua are planned; hence, imagery is scheduled to be available in the future. ET is closely related to landscape "greenness," as estimated by satellite vegetation indices, which integrate leaf area index, plant chlorophyll content, and fractional cover into a single predictive variable. Hence, it is not necessary to digitize separate landscape units to estimate ET to estimate irrigation requirements. As long as the target area is large enough to sample with MODIS imagery (each pixel is 6.25 ha), it should provide reliable estimates of landscape water requirements. This finding is in line with those of Johnson and Belitz [51] that employed Landsat to estimate urban irrigation rates. They stated that the monthly irrigation rate for fully irrigated urban sites in large sizes could be calculated using NDVI, weather data, and scaling functions. Additionally, Liu *et al.* [52] employed Landsat 5 data to estimate actual ET in the Oklahoma County. Their findings approved the accuracy of remote-sensing-based ET measurements validated by flux towers and SWB.

Author Contributions: Hamideh Nouri conceived, designed and performed the experiment and wrote the paper; Hamideh Nouri and Edward Glenn analyzed the field and remote sensing data and contributed to write these sections; Hamideh Nouri and Sattar Chavoshi Borujeni established the experiment in the field and collected field data regularly; Sina Alaghmand and Behnaz Noori contributed in analyzing climate data and interpretation of NMM readings; Simon Beecham supervised the project; Paul Sutton contributed by writing and editing some sections; Pamela Nagler contributed by applying her ET model in agriculture and riparian lands to test it in urban parklands (VG) and helping to be sure the scaling up worked and contributed to editing the final manuscript draft. We thank the USGS peer reviewers as well. Ed Glenn paid all fees associated with publishing this manuscript.

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