Landscape and Urban Planning 190 (2019) 103613

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

The blue water footprint of urban green spaces: An example for Adelaide, Australia

Hamideh Nouri[a,b,*], Sattar Chavoshi Borujeni[c], Arjen Y. Hoekstra[b,d]

[a] Division of Agronomy, University of Göttingen, Von-Siebold-Strasse 8, 37075 Göttingen, Germany
[b] Department of Water Engineering and Management, Faculty of Engineering Technology, University of Twente, 7500 AE Enschede, The Netherlands
[c] Soil Conservation and Watershed Management Research Department, Isfahan Agricultural and Natural Resources Research and Education Centre, AREEO, Isfahan, Iran
[d] Institute of Water Policy, Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore

ARTICLE INFO

Keywords:
Water scarcity
Urban water
Smart green city
Evapotranspiration
Urban greenery
Blue water footprint

ABSTRACT

The development of 'greening' cities introduces an uneasy tension between more green spaces and the increased use of scarce blue water resources to maintain this greenness, particularly in dry regions. This paper presents the first estimate of the blue water footprint (WF) of urban greenery. We estimated total water consumption of a 10-hectare parkland in Adelaide, South Australia. Evapotranspiration of the urban vegetation was estimated by monitoring soil water inflows, outflows, and storage changes at an experimental site representing different species, microclimates, and plant densities, the most critical parameters affecting water use. The total WF was estimated at 11,140 m^3/ha per year, 59% from blue water (irrigation), and 41% from green water (rainwater), with the highest water consumption in summer. The dependency on blue water resources for maintaining the greenery varied from 49% in October to 67% in March. Even in the wet period of the year, there was a significant blue WF. Given the lack of blue water resources to allocate for further greening the city in an arid environment, we suggest an integrated adaptive management strategy to maintain available greenery and expand green spaces with a minimum of extra pressure on blue water resources.

1. Introduction

The world's urban population grew from 30% of the total in 1950 to 56% in 2019 and is expected to reach 68% by 2050 (UN, 2017). As urban areas continue to grow, green spaces in cities are getting increasingly valued (Chang et al., 2017; Hosaka & Numata, 2016; Palmer, 2018). Urban green spaces are key elements in maintaining and improving human health and wellbeing and provide a range of other environmental, social, and economic benefits and services (Li, Sutton, Anderson, & Nouri, 2017; Li, Sutton, & Nouri, 2018; Van den Bosch & Nieuwenhuijsen, 2017).

Historically, the priority of most municipalities has been to develop grey infrastructures such as high-rises, roads, bridges, and energy networks rather than green spaces and infrastructures. In recent years, increasing attention has been given to green space infrastructure and efforts are being undertaken to integrate grey and green infrastructures (Angelstam et al., 2017; Anguluri & Narayanan, 2017; Meerow & Newell, 2017). Most cities have adopted plans to be greener to enhance their resilience, livability, and health. For instance, Vancouver has adopted a plan to become the greenest city in the world by 2020 (City of Vancouver, 2012). In Australia, the national *202020 Vision Plan* has been launched to create 20% additional green spaces in urban areas by 2020 (Bun, Jones, Lorimer, Pitman, & Thorpe, 2015; Li et al., 2017). The majority of decisions and policies to green cities imply an increase in the consumption of blue water resources (water from groundwater or surface water) to irrigate these green spaces in times of green water (precipitation) deficits. This is potentially a problem in arid and semi-arid environments, where blue water is generally a scarce resource, and even more so under climate change, which implies that many dry regions and particularly dry periods of the year become drier (Bates, Kundzewicz, Wu, & Palutikof, 2008; Degefu et al., 2018; Velpuri & Senay, 2017).

There is an uneasy tension in arid and semi-arid environments between 'greening a city' by creating more green spaces and the increased use of scarce blue water resources to maintain this extended greenness. Since urban greenery generally consumes a mix of green water (rainwater) and blue water (irrigation water abstracted from rivers, lakes, reservoirs, ponds, and aquifers), greening a city may come at a price of increasing water scarcity. Maintaining the greenness and aesthetics of urban green spaces is very resource-intensive and sometimes

* Corresponding author at: Division of Agronomy, University of Göttingen, Von-Siebold-Strasse 8, 37075 Göttingen, Germany.
E-mail address: hamideh.nouri@uni-goettingen.de (H. Nouri).

https://doi.org/10.1016/j.landurbplan.2019.103613
Received 11 June 2018; Received in revised form 2 July 2019; Accepted 5 July 2019

impossible. Given the importance of greening cities, a trade-off will have to be made between becoming 'greener' and reducing blue water consumption.

Most urban green spaces in arid to semi-arid climates experience hot and dry seasons with frequent and severe droughts. It means that maintaining green spaces all-year-round requires irrigation (blue water). Some cities have introduced drought response strategies such as allowing green spaces to dry out during the hot period. For instance, some city councils in South Australia terminated watering green spaces in about 60% of their green urban landscape in summer (Daniels, Hodgson, & Hardy, 2010; Government of South Australia, 2010; Schebella, Weber, Brown, & Hatton, 2014).

The literature on the water use of urban green spaces focusses either on the irrigation water demand of residential urban landscape (Hilaire et al., 2008) or on the evapotranspiration from green spaces (Nouri, Beecham, Kazemi, & Hassanli, 2013; Nouri, Beecham, Anderson, Hassanli, & Kazemi, 2015). Whereas studies of the former type focus on blue water needs, studies of the latter type consider both green and blue water consumption but do not differentiate between them. Studies on irrigation water demand of urban greenery focus on understanding and explaining this demand and/or exploring how to reduce this demand. For instance, Domene and Saurí (2006) assess the water use of residential green spaces in response to vegetation species, housing type, and the number of residents and their income. Wentz and Gober (2007) investigate the significance of residents number, lot size and landscape practices on the water demand detached single-family residential units. Guhathakurta and Gober (2007), assess the impact of the urban heat island effect on residential water use. Endter-Wada, Kurtzman, Keenan, Kjelgren, and Neale (2008) estimate the irrigation demand of the backyards of residential and business units of the urban Utah community. Balling, Gober, and Jones (2008) measured residential water uses and their response to atmospheric conditions. Salvador, Bautista-Capetillo, and Playán (2011) evaluate the irrigation performance of private household landscapes using bi-monthly water billing records in Zaragoza, Spain. Mini, Hogue, and Pincetl (2014) estimate irrigation demand of the residential landscape using remotely-sensed vegetation and water billing data. Ouyang, Wentz, Ruddell, and Harlan (2014) compare the relationship of residential water use of single-family households and census data in the Phoenix metropolitan area. Reyes-Paecke, Gironás, Melo, Vicuña, and Herrera (2019) determines the water consumption for irrigation of green spaces and residential gardens in Santiago, Chile and compares this consumption with the expected vegetation water requirements estimated using a hydrological model. There are few studies on larger-scale urban green spaces (larger than backyards), which is the scale of interest when we consider the effect of greening cities. Gober et al. (2009) investigated the cooling effect of watered urban landscapes. Volo, Vivoni, and Ruddell (2015) introduced an ecohydrological method of water saving through optimized irrigation of urban green spaces.

Studies on evapotranspiration from green spaces focus on estimating potential and actual evapotranspiration using field measurements, models or remote sensing and/or explore irrigation requirements from the gap between potential and actual evapotranspiration. For instance, Nouri et al. (2016) determined the evapotranspiration of urban parkland in Adelaide using field-based (Nouri, Beecham, Hassanli, & Kazemi, 2013) and remote sensing-based approaches (Nouri, Beecham, Anderson, & Nagler, 2014). Shojaei, Gheysari, Nouri, Myers, and Esmaeili (2018) estimated the water requirements of two urban parks using factor-based approaches in the city of Isfahan, Iran. Marchionni, Guyot, Tapper, Walker, and Daly (2019) measured the water balance of three urban green reserves in the metropolitan of Melbourne, Australia.

Previous studies on blue water use for urban greenery focus on *abstracted* blue water, the water required to irrigate, rather than *consumed* blue water. Blue water *abstraction* refers to the water withdrawn from groundwater, streams, lakes or reservoirs. Blue water *consumption* is the terminology used by hydrologists to refer to the part of the water applied to the landscape that transpires through the vegetation or evaporates from the soil. In order to assess the contribution of water use to water scarcity in a catchment, it is more useful to look at the amount of water consumed than to consider the amount of water abstracted, because a part of the abstracted blue water that is applied to the landscape will infiltrate and thus return to groundwater and streams. This return water (non-consumed water) is available for use again and thus doesn't contribute to water depletion.

Besides, most urban water use studies exclusively focus on blue water use, leaving green water use out of the scope. Studies that do include green water use consider total water consumption of urban greenery, which refers to the sum of green and blue water evapotranspiration from the green spaces. These studies study total ET from the landscape but do not distinguish between green and blue water consumption. We thus lack studies that study both and distinguish between green and blue water consumption.

The novelty of the current manuscript is that it is the first to focus on the blue water consumption of urban green spaces rather than on water abstracted to irrigate green spaces. We do this by using the water footprint, which measures both and distinguishes between the consumption of green and blue water resources. This paper thus combines green and blue water footprint accounting for urban green spaces. Whereas the water footprint concept has been applied to a variety of water uses, from agriculture and forestry to industry and households, this is the first application to urban green spaces.

The aim of this paper is to estimate the blue water footprint to maintain the green areas within a city in an arid/semi-arid environment and put the findings in the context of other urban water needs. As a case study, we consider the city of Adelaide in Australia. Most studies of water footprint assessment so far were carried out at the catchment, national or global scale, with less attention to urban studies (Hoekstra, Chapagain, & Zhang, 2016; Hoekstra, 2017). The urban water footprint studies to date focused on estimating the internal versus external water footprint of urban consumption, i.e. the volume of water resources used within the area of the municipality versus the volume of water used in other locations to produce goods and services consumed by the urban population (Ahams et al., 2017; Ma, Xian, Zhang, Zhang, & Ouyang, 2015; Mahjabin, Garcia, Grady, & Mejia, 2018; Paterson et al., 2015; Rushforth & Ruddell, 2015; Rushforth & Ruddell, 2016). Regarding the internal water footprint in the city, none of the previous urban water footprint studies explicitly included the water consumption for maintaining urban greenery. A number of other studies focused on the water footprint of urban food consumption and the role of diets (Bosire et al., 2017; Vanham, del Pozo et al., 2016; Vanham, Mak, & Gawlik, 2016). Another study focused on the water footprint of urban farming (Mark, Michael, Thoreau, & Nicholas, 2015), which is also green space in the urban environment, but urban agriculture forms only a small fraction of the total urban green space in most cities (McLain, Poe, Hurley, Lecompte-Mastenbrook, & Emery, 2012; Russo, Escobedo, Cirella, & Zerbe, 2017). The current study is the first on the blue water footprint of maintaining urban green spaces.

2. Method and data

2.1. Case study

The world's ten most livable cities in 2017, according to the Economist Intelligence Unit (EIU), were Melbourne, Vienna, Vancouver, Toronto, Adelaide, Calgary, Perth, Auckland, Helsinki, and Hamburg (EIU, 2017), based on criteria like healthcare, stability, culture, environment and green infrastructure. The presence of green areas is an essential factor in ending up high on the list of livable cities (EIU, 2017). The World Health Organization (WHO) has suggested a minimum of reachable, safe and usable 9 m^2 of green space per person in cities; the ideal is 50 m^2 (Morar, Radoslav, Spiridon, & Păcurar, 2014;

WHO, 2010). Structure, characteristics, spatial distribution, and accessibility of these green spaces are very important to achieve sustainability goals in smart green cities (Badiu et al., 2016; Wüstemann, Kalisch, & Kolbe, 2017). Melbourne and Vienna ranked top on the list, with 163 and 125 m^2 of green spaces per capita, respectively (Aldous, 2010; Morar et al., 2014). Many cities in the world provide less than the minimum as proposed by the WHO, such as Istanbul, Tokyo and Buenos Aires, with green areas of 6.4, 3.0 and 1.9 m^2 per person, respectively (Morar et al., 2014).

Adelaide, the capital of South Australia, has regularly been ranked as one of the world's most livable cities. The greater metropolitan area of Adelaide is home to 75% of South Australia's population. In 2016, the Government of South Australia and the Adelaide City Council have committed to making Adelaide one of the first carbon-neutral cities in the world (Adelaide City Council, 2016; Robinson & Liu, 2015). In order to achieve this goal, an integrated strategy of emission reduction has been adopted, which includes the planning for a greener city alongside a range of other actions.

Adelaide is entirely enclosed by an enormous greenbelt, namely Adelaide Parklands. These Parklands, including a diverse mix of landscapes and open woodlands, comprise a total of 29 parks with an approximate area of 720 ha, of which 40% is irrigated (ALPA, 2016). A recycled wastewater project, Glenelg to the Adelaide Parklands (GAP), sourcing from the secondary effluent from an existing wastewater treatment plant, transports recycled wastewater to irrigate the Parklands. The GAP project was designed to provide more than 3.8 million m^3 of high-quality recycled wastewater annually for the city of Adelaide including the Parklands. Pressurized membrane filtration is used to meet the design capacity required by the demand of the treatment plant as well as the required water quality. An automatic pressurized irrigation system is used in the Parklands using different types of sprinklers including Hunter I-31, Hunter I-20 ultra and Hunter institutional, and different drippers to sustain soil moisture. A full irrigation strategy is applied, which means that irrigation is done to fully fulfil vegetation water requirements. Adelaide City Council, which manages the Parklands, reported an irrigation efficiency of 70% for the entire park and distribution efficiency of 75% for turf grasses and 60% for trees in the shadowing areas (Nouri, Beecham, Hassanli, & Kazemi, 2013).

The Greater Adelaide water supply system is complex and offers a diversity of supply sources including rivers, surface water reservoirs, groundwater, rainwater, storm water, and alternative water resources like wastewater. Around the years 2007–2008, 93% of the total potable water supply was sourced from rivers and reservoirs (primarily from the Murray River, which contributed 85%), 7% from groundwater and less than 1% from desalinated water (DEWNR, 2014). Adelaide has relatively little water storage to carry water supplies over from year to year. The recent millennium drought showed that the Murray River does not provide a steady, predictable and reliable flow.

Fig. 1 shows the long-term averages of the monthly mean temperature and monthly mean precipitation for the Parklands, for the period 1977–2016, and the same variables for the study period of December 2011 to November 2012. Temperature in the study period followed the long-term average, but precipitation came in a different pattern than the long-term average, with particularly above-average rain in February-March and less in June.

We selected a 10-hectare experimental site in the Adelaide Parklands that represents the heterogeneity of species, microclimates, and vegetation densities within the Parklands, the most critical parameters affecting water use of urban vegetation. At this site, in-situ measurements took place in four zones. These four zones represent the combinations of two different landscapes and two different soils. Two major landscapes were distinguished: MG (primarily covered with turf grasses with few trees and shrubs) and MT (mostly trees and shrubs with intermittent turf grasses). We distinguished two soil zones: S1 (soil salinity < 1.2 dS/m) and S2 (soil salinity of 1.2–2 dS/m). Sampling positions were chosen in each of these four zones, in order to capture the heterogeneity of key variables. The 10-hectare experimental site hosts over 70 exotic and native species of trees, shrubs, and turf grasses – the most dominant vegetation in the Parkland- impacted by urban features like buildings, sidewalks, and parking lots, introducing a complex microclimate to the urban greenery – a comparable pattern for the whole parklands. The required tools and equipment including one weather station, four lysimeters, and twelve Neutron Moisture Meter probes were installed in these four zones. Given the selection of a representative set of sampling places (given the diversity of vegetation types), it was assumed that the average of the four sampling places could be taken as an average for the Parklands as a whole.

2.2. Water footprint of urban green spaces

The water footprint (WF) of urban green spaces is defined as the volume of rainwater and irrigation water being consumed by these green spaces, i.e. the volume of water evaporating. This WF can be expressed as a volume per hectare or as a total volume when aggregated over the total area of green spaces. The amount of evaporated rainwater is called the green WF; the volume of evaporated irrigation water or evaporated groundwater from capillary rise is called the blue WF. The definitions used are in line with the global water footprint assessment standard (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011). The WF of urban greenery as we apply it here is similar to the WF of croplands (Mekonnen & Hoekstra, 2011) or the WF of forestry (Schyns, Booij, & Hoekstra, 2017). The term evaporation refers to the full evaporative flow, including soil evaporation, evaporation of the intercepted water on leaves, and plant transpiration. Total evaporation – often called evapotranspiration (ET) – is the sum of green ET and blue ET. It is only total ET that can be measured; the partitioning into green and blue ET refers to the origin of the evaporated water and can be estimated by tracing the origin of the water in the soil (Hoekstra, 2019).

2.2.1. Total ET of green spaces

Total ET of urban greenery was measured by the Soil Water Balance (SWB) method quantifying all inflows, outflows and storage changes (Campos et al., 2016; Glenn et al., 2013). ET was calculated as the sum of the inflows minus the sum of the (other) outflows and the soil moisture storage increase, using the measurements from the experimental site (Nouri et al., 2016).

$$ET = P + I + CR - RO - D - \Delta S \tag{1}$$

The inflows are precipitation (P), irrigation (I) and capillary rise (CR), and the outflows are evapotranspiration (ET), runoff (RO), and drainage (D). ΔS refers to soil moisture change. The SWB components were collected for 12 months on a monthly basis.

Meteorological data have been acquired from two weather stations: an automatic weather station (Davis Vantage Pro2) installed in the Parklands and a quality controlled weather station run by the Australian Bureau of Meteorology at Kent Town (34.92° S, 138.62° E, elevation 48 m) located 2.9 km from the Parklands. Meteorological data in this study are the average values of these two stations. Monthly drainage was calculated as the average records of in-situ percolation measurements from pan lysimeters in the Parklands. A comprehensive description of installation, calibration, collection methods, and recorded data are available in Nouri, Beecham, Hassanli, and Ingleton (2013). The highest monthly drainage was recorded in winter (mean of 67.1 mm in July) and the lowest at the end of spring and the whole summer (less than 1 mm from December 2011 to March 2012 and later in November 2012). Groundwater levels were measured every three months through monitoring wells to account for the upward contribution to soil moisture through capillary rise. Capillary rise and runoff were reported null during this study (Nouri, Beecham, Hassanli, & Ingleton, 2013). Irrigation data were obtained from the local authority, Adelaide City Council. As expected, most irrigation was applied in the

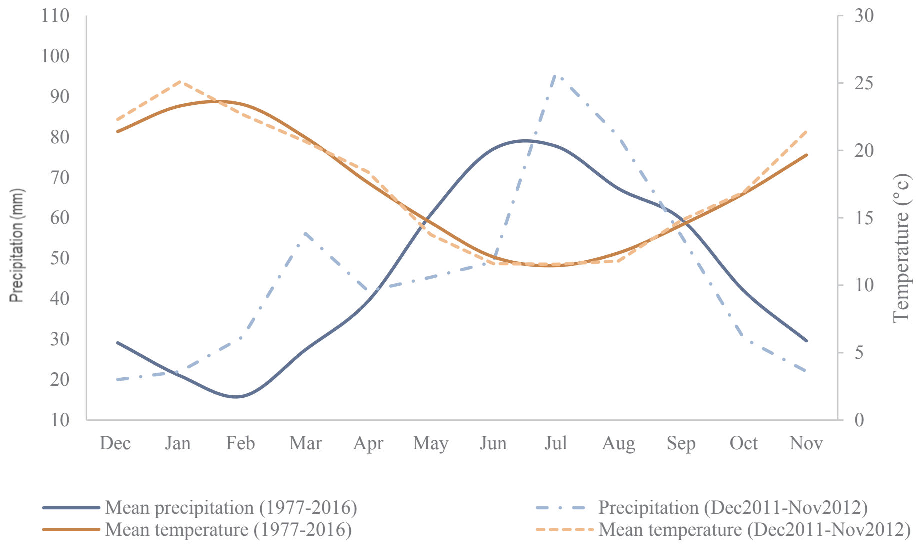

Fig. 1. Long-term averages for monthly mean temperature and monthly precipitation in Adelaide Parklands (1977–2016), and the same variables during the study period (Dec. 2011-Nov. 2012).

dry and hot summer, from December to February, and no irrigation took place during the wet and moderate winter. Soil moisture content was measured on selected dates during the study period using an in-situ method of Neutron Moisture Meter (NMM) down to 4-meter depth at 12 points. Recorded data of soil moisture showed that smart irrigation in the Parklands could successfully manage a minimum variation of soil moisture over the year, with soil moisture ranging 0.262 to 0.293 $cm^3 \cdot cm^{-3}$.

The highest ET values were found in the summer time, from December to February, and the lowest ET values in wintertime, in June (Table 1).

2.2.2. Partitioning into green and blue ET

By tracking the volumes of green versus blue water inflows into the effective root zone of urban vegetation and by keeping track of the color composition of the water in the soil over time, the total ET could be attributed to green and blue water sources, following the method described by Hoekstra (2019) and earlier applied for instance by Chukalla, Krol, and Hoekstra (2015), Zhuo, Mekonnen, Hoekstra, and Wada (2016) and Karandish and Hoekstra (2017). These earlier studies applied the method to distinguish between green and blue ET from croplands, but the same method applies to urban green spaces. The method is based on keeping a time record of the fractions of green and blue water in the soil. Infiltration of rainwater contributes to the green water content in the soil, while infiltration of irrigation water contributes to the blue water content of the soil. Capillary rise from groundwater to the unsaturated soil contributes to the blue water content as well. The green/blue water ratio in all outflows from the soil at a certain moment (evapotranspiration and drainage) is assumed to equal the green/blue ratio of the soil moisture at that time. To partition soil moisture into a green and two blue components, the following equations are used:

$$\frac{\Delta S_g}{\Delta t} = P - \left(\frac{S_g}{S}\right)(D + ET) - \left(\frac{P}{I + P}\right)RO \tag{2}$$

$$\frac{\Delta S_{b,I}}{\Delta t} = I - \left(\frac{S_{b,I}}{S}\right)(D + ET) - \left(\frac{I}{I + P}\right)RO \tag{3}$$

$$\frac{\Delta S_{b,CR}}{\Delta t} = CR - \left(\frac{S_{b,CR}}{S}\right)(D + ET) \tag{4}$$

where Δt is the time step of the calculation (one month in this case), S_g the green part of the soil moisture, $S_{b,I}$ the blue part of the soil moisture originating from irrigation, and $S_{b,CR}$ the blue part of the soil moisture originating from capillary rise.

Per month, ET_g, $ET_{b,I}$ and $ET_{b,CR}$ are calculated as fractions of total ET, based on the fractions of soil moisture in that month that are green water, irrigation-related blue water, or capillary rise related blue water:

$$ET_g = \left(\frac{S_g}{S_g + S_{b,I} + S_{b,CR}}\right)ET \tag{5}$$

$$ET_{b,I} = \left(\frac{S_{b,I}}{S_g + S_{b,I} + S_{b,CR}}\right)ET \tag{6}$$

$$ET_{b,CR} = \left(\frac{S_{b,CR}}{S_g + S_{b,I} + S_{b,CR}}\right)ET \tag{7}$$

For partitioning drainage into different color components, we followed the same approach. The green/blue composition of initial soil moisture for each measuring location was determined iteratively, by first assuming a green/blue water ratio of 50%/50% and then taking the final soil moisture composition of the first run as initial soil moisture composition for a second run, etc., until the ratio had converted to a certain figure.

Table 1
Soil water balance components in Adelaide Parklands in the period from December 2011 to November 2012.

Water balance component	Dec 2011	Jan 2012	Feb 2012	Mar 2012	Apr 2012	May 2012	Jun 2012	Jul 2012	Aug 2012	Sep 2012	Oct 2012	Nov 2012
Precipitation (mm)	20.0	22.0	30.6	56.1	41.9	45.3	49.1	96.0	80.1	55.6	30.2	22.1
Irrigation (mm)	119.3	145.1	159.9	90.7	49.3	46.4	0.0	0.0	0.0	0.0	44.6	65.3
Drainage (mm)	0.3	0.1	0.1	0.3	3.5	8.6	37.3	67.1	11.2	35.4	12.3	0.0
Soil moisture increase (mm)	−45.0	31.0	42.3	29.8	−23.1	12.1	−11.6	−16.3	−14.6	−14.0	13.6	−25.0
ET (mm)	183.9	136.0	148.2	116.7	110.7	71.0	23.4	45.2	83.5	34.1	48.8	112.3

[*] Capillary rise and runoff were null.

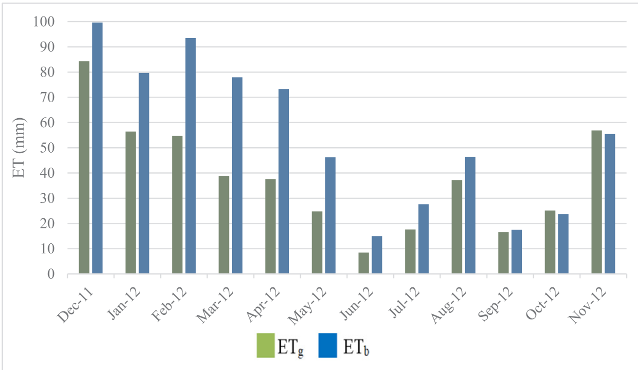

Fig. 2. The green and blue components of ET in Adelaide Parklands (Dec. 2011 – Nov. 2012).

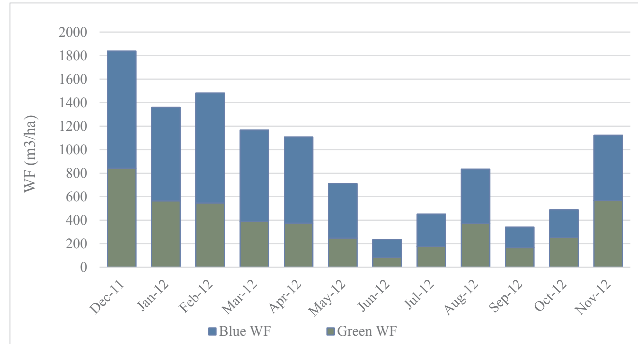

Fig. 4. The green and blue water footprint of maintaining the Adelaide Parklands, from December 2011 to November 2012.

The green and blue WF of urban green spaces were calculated by converting green and blue ET (in mm) into a water volume (m^3) per unit area (hectare).

3. Results

3.1. Green and blue ET

Estimated green and blue ET per month are shown in Fig. 2. Over the study period, both ET_b and ET_g varied by season – high in the summer months and low in the winter months. ET_b was significantly larger than ET_g from December to August and about equal from September to November. Highest ET_b values were found in summer, with the maximum of 99.6 mm in December and 93.5 mm in February. Lowest ET_b values were found in winter, with a minimum of 14.9 mm in June.

Fig. 3 shows that total and blue ET vary within the year with temperature, being high in summer and low in winter. In winter, precipitation is relatively high, while ET is relatively low. There was a jump in both blue and total ET in August, resulting from a precipitation peak in July.

3.2. Green and blue water footprint of maintaining Adelaide Parklands

The monthly green and blue WF per hectare of the Parklands is plotted in Fig. 4. The hot and dry summer resulted in a high total WF compared to the cold and wet winter. From summer to winter, a sharp drop is seen in the total WF and blue WF and a moderate decrease in the green WF. In winter, there is no irrigation, so the blue WF in this period refers to evaporation of blue water stored in the soil from irrigation in previous months. An unexpected high rainfall in July resulted in the highest total, green and blue WF in the wet season (August).

About 59% of the annual total WF was blue (6560 m^3/ha), and about 41% was green (4580 m^3/ha). The dependency on blue water for maintaining the green landscape varied from 49% in October (the end of the wet season) to 67% in March (the end of the dry season).

The annual total WF is estimated at 11,140 m^3/ha (i.e. 1114 mm), of which 42% took place in the summer (Dec-Feb), 27% in autumn (Mar-May), 14% in winter (Jun-Aug), and 17% in spring (Sep-Nov). December to February, which are the hottest months of the year in South Australia, with maximum daily temperatures exceeding 40 °C and monthly rainfall of less than 30 mm in 2012, have the highest total WF and blue WF. Autumn started with a relatively hot March, with a maximum temperature of 35 °C and average maximum temperature of 26.2 °C. Even though rainfall in March was high compared to the long-term average for March (see Fig. 1), the green inflow could not fulfil the water demand of the vegetation – which was measured by the SWB approach and extensively discussed by (Nouri et al., 2016) – so blue WF was still relatively high. From April onward, the weather started cooling down; with the cold winter and dormancy of some species, water demand was less, and consequently, the total, blue and green WF show a considerable decline. In spring, a higher temperature that accompanies lower rate of rainfall resulted in a significant rise in the WF. Although there was no irrigation from June to September, blue WF contribution in the total WF is not negligible.

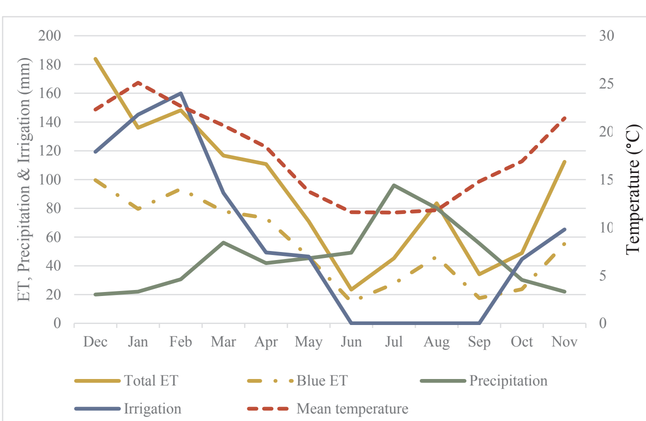

Fig. 3. Monthly total ET, monthly blue ET, monthly precipitation, monthly irrigation and monthly mean temperature during the study period (December 2011 to November 2012) in Adelaide Parklands.

4. The blue WF of Adelaide Parklands compared to the total urban water supply

The average blue WF of the Parklands was calculated 6560 m^3/ha per year to maintain the health and greenness of urban greenery in Adelaide. With a total Parklands area of 720 ha, of which 40% irrigated, this implies a total blue WF of Adelaide Parklands of 1.89 million m^3/y, about half of the GAP treated wastewater capacity. With a population of 1.3 million (in 2014), the Parklands alone provide about 5.5 m^2 of greenery per capita.

The water supply of Adelaide was 256.4 million m^3/y during 2014–2015 (BOM, 2015) as reported in Table 2.

Table 2
Urban water system inflows in Adelaide 2014–2015.

Urban water system inflows (10^3 m^3/y)	
Surface water	135.143
Recycled wastewater–inter-region water treatment plant	22.725
Water supply – inter-region	4.031
Recycled wastewater	94.463
Total	256.362

Table 3
Ratio of the blue water consumption of urban greenery to Adelaide's total urban water supply for the cases of a minimum size of greenery (9 m^2/capita) and ideal size of greenery (50 m^2/capita).

	WF per unit of urban greenery ($m^3/m^2/y$)	WF per capita (m^3/y/capita)		WF of the whole population (million m^3/y)		Ratio of blue WF of greenery to current urban water supply	
		for the minimum size of greenery	for ideal size of greenery	for the minimum size of greenery	for ideal size of greenery	for the minimum size of greenery	for ideal size of greenery
Total WF	1.11	10.0	55.7	13.1	72.6	–	–
Blue WF	0.66	5.90	32.8	7.69	42.7	3.0%	16.4%

When we scale our Parklands findings to Adelaide as a whole, we can roughly estimate the WF of urban greenery for a minimum size of 9 m^2 per capita and the ideal size of 50 m^2 per capita (Table 3). In both cases, we can also estimate the WF of greenery for the population as a whole, as well as the ratio of the blue WF of urban greenery to the current total blue urban water supply.

In Adelaide – and cities with similar climate and landscape – establishing and maintaining the ideal size of urban greenery of 50 m^2/capita requires allocating a significant share of urban water flow to this purpose. In this case, to achieve the ideal size of urban greenery, 16.4% of the total urban blue water flow would need to be allocated to watering green spaces.

The average indoor household water use in South Australia has been estimated to be 135 L/day per capita (Arbon, Thyer, Hatton, & MacDonald, 2014), which for Adelaide, with a population of 1.3 million, means a total indoor water use of 64.1 million $m^3\ y^{-1}$. Given an estimated total WF of 72.6 million $m^3\ y^{-1}$ for an ideal size of urban greenery, we find that maintaining urban green spaces is a large contributor to the total urban WF and should not be ignored in WF studies of urban areas.

The water accounts for Adelaide show that its green spaces heavily rely on blue water resources, even in the wet period of the year. The tension between the blue water demand for maintaining the green spaces and the water demands for other purposes in the city will become worse if water demands further increase or if water availability gets reduced through climate change.

5. Discussion and conclusion

As illustrated by the case of Adelaide, the tension between greening initiatives in cities in arid and semi-arid regions and the growing blue water scarcity around cities urges for a deeper look into this topic. The necessity of conserving vegetation in cities is unquestionable. However, shortage of blue water resources, as well as the high opportunity cost of blue water, cause a real challenge to find a balance between "greening" and "water saving".

Water accounts, whether they be at the state or municipal level, generally entirely ignore the availability and use of green water resources. Considering both green and blue water resources as in the current study could inform decision-makers on the availability of each source and its seasonal changes. The blue water demand for maintaining urban green areas – similar to the blue water demand in agriculture – is always the result of a lack of rain (green water), so both water resources are related. However, optimal irrigation – to achieve maximum plant growth – is not a necessity. Green areas can also be maintained with deficit irrigation (causing some water stress to the plants), with supplementary irrigation (providing water only during the most critical periods of drought), or depending on the climate, soil, topography and vegetation even without irrigation at all, particularly when choosing to have native plant species. Water-efficient irrigation systems and techniques like drip irrigation can also reduce the blue WF, while still maintaining some level of greenness. In addition, proper mulching of the soil can also reduce ET significantly, thereby reducing the irrigation needs, as has been extensively shown for crop production already (Chukalla et al., 2015). Using (treated) wastewater or storm water to irrigate urban greenery could reduce urban water scarcity as well, but since these forms of water can also be used for other purposes in the city, this does not reduce the overall competition over scarce blue water resources.

Water footprint assessment (WFA) could help landscape architects to choose the appropriate turf, shrub and tree species in landscape design, considering their water demand and drought tolerance. Selecting appropriate vegetation species based on the availability of green water resources is very important. Drought-tolerant native species with minimum water demands that can survive with available green water resources are more appropriate. Urban forests are generally more water efficient than turf grasses, especially manicured lawns that are developing these days to meet public's expectation of designed landscapes. Selecting the appropriate plant species is not limited to drought-tolerant species but also include their patterns of water use. Furthermore, as pointed out by McDonnell (1990), the rooting depth of a species matters as well: plants (e.g. trees) that have access to deeper water sources (long residence time), will depend less on shallow water (short residence time).

Applying the concept of water sensitive urban design (WSUD) can similarly help greening cities while not increasing the pressure on blue water resources. One may think of rainwater gardens, adaptive infrastructure such as swales, constructed ponds and wetlands, and rainwater tanks. The potential and limitations of WSUD for water conservation and development of green spaces were comprehensively discussed by Chavoshi, Pezzaniti, Myers, and Sharma (2017), Sharma et al. (2016), Myers et al. (2014), and Sharma, Pezzaniti, Myres, Chacko, Tjandraatmadja, Cook, Chavoshi, Kemp, Leonard, Koth, and Walton (2013).

We suggest that an integrated framework of WSUD and WFA could be a decentralized local solution to enhance green water productivity in green cities in arid to semi-arid regions. The challenge is to make most benefit of available green resources with least reliance on blue water resources.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2019.103613.

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