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Evaporative Cooling Effect of Water-Sensitive Urban Design: Comparing a Living Wall with a Porous Concrete Pavement System

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Abstract: Living walls are becoming a widely used water-sensitive urban design technology that can deliver various economic, social and environmental benefits. One such benefit is to cool the surrounding environment through the process of evapotranspiration. This study measured the evapotranspiration from an instrumented prototype-scale living wall and calculated the resulting evaporative cooling effect. The range of the measured evapotranspiration rates from the living wall was from 41 to 90 mL/mm per plant pot. This equated to latent heat of vaporisation values from 171 to 383 MJ/month/m^2. This was then compared with the performance of a non-vegetated water-sensitive urban design technology, namely, a porous concrete pavement. For a typical summer month in a warm temperate climate, it was found that a porous concrete pavement system only had between 4 and 15% of the cooling effect of an equivalent living wall.

Keywords: water-sensitive urban design; living wall; porous pavement; evaporative cooling; urban heat island

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1. Introduction

The water-sensitive urban design (WSUD) is a systems approach that can be applied across various scales of urban development such as residential homes, roads, car parks, sub-divisions, multi-storey buildings, commercial and industrial areas and public land. It is important to note that various other terminologies exist including nature-based solutions (NBS), integrated urban water management (IUWM) and green infrastructure, although the term most commonly used in Australia is WSUD. Green roofs, living walls, permeable pavements and bio-retention systems are examples of commonly used WSUD technologies that are designed to reduce the flood risk, improve water quality and enhance urban biodiversity [1]. Figure 1 shows a 1200 m^2 living wall in Sydney, Australia.

The general term *green wall* describes any wall that is covered in vegetation. Similar terms include the vertical greenery system, vertical garden, bio-shader and vertical landscaping. Depending on the growing method, green walls can be sub-classified into living walls and green façades [2]. A living wall (LW) has vegetation planted and irrigated on a structure that is attached to the wall. On these structures, the vegetation is planted in felt pockets, modular pots or planter boxes. In contrast, the vegetation in a green façade has its roots planted in the ground, and only its stems, leaves and flowers grow vertically on the wall [3]. The focus of this study is on living walls rather than on green façades.

The plants in living walls convert solar radiation and sensible heat into latent heat through transpiration. Through this process, living walls can mitigate the Urban Heat Island (UHI) effect by generating a microclimate [4]. For instance, temperature differences recorded between a bare control wall and a living wall were up to 15 °C in summer in a study conducted in Adelaide, Australia [5]. In a similar experimental study conducted in Northern and Central Italy, temperature differences between 12 °C and 20 °C were recorded between a living wall and its bare control wall [6].

Figure 1. Sydney's Largest Living Wall at One Central Park.

Evapotranspiration (ET) is a very important process in living walls. The ET rate is often controlled by climatological and meteorological factors including radiation, temperature, wind and humidity, in addition to substrate type, available moisture, and plant behaviour [7–9]. In recognising the complicated multidisciplinary nature of green infrastructure and, particularly, living walls, plans to mitigate the urban heat island can be expected to be developed differently according to local climates.

Adelaide's hot and dry climate is challenging for any green infrastructure, and consequently native and drought-tolerant plants have often been preferred in previous green infrastructure studies [10]. However, the native plants of South Australia are often hardy and drought-tolerant because they have lower ET rates than more lush vegetation. This raises the issue of a trade-off between resilient LWs designed with drought-tolerant plants versus effective LWs with high irrigation and ET rates.

While previous studies have confirmed the microclimatic benefit of LWs due to their ET processes [11,12], there has been only one previous attempt to quantify the evaporative cooling of LWs through the latent heat of vaporisation [13]. This study seeks to investigate the potential for ET-based microclimate cooling through the latent heat of vaporisation from an LW.

A porous concrete pavement, like a living wall, is a water-sensitive urban design technology that can have a cooling effect on its surrounding environment. Compared to conventional impermeable concrete or asphalt pavements, porous concrete pavements permit the infiltration of stormwater as well as the evaporation of the infiltrated water through the pavement's porous structure [14]. Li et al. [15] observed that this evaporation rate depends on air temperature, relative humidity, water temperature, moisture content, air void content, air void size and connecting structure. In a laboratory study, Yang et al. [16] measured the evaporation from porous pavement systems and found that the measured latent heat flux ranged from 27 to 240 W/m^2. They concluded that this evaporative cooling effect only occurred after rainfall when water was available in the upper 13 mm of the porous concrete pavement. They also stated that on dry days, there would be no water in the upper 13 mm of the porous concrete system and hence no cooling effect.

The objective of this research was to measure the evapotranspiration from an experimental living wall in order to estimate its evaporative cooling effects in summer. This was then compared with evaporative cooling effects that have been recently reported from porous concrete pavements, which are a type of non-vegetated water-sensitive urban design system.

2. Materials and Methods

An instrumented living wall of width 2.4 m and height 3.0 m was mounted on a west-facing unroofed brick atrium wall of a university building in Adelaide, South Australia (Figure 2). The experiment was conducted over 18 months, from November 2016 to May 2018. The city of Adelaide has a temperate Mediterranean climate (Csa, warm temperate summer–dry hot summer) in accordance with the Köppen–Geiger climate classification system [17]. The city has an annual average rainfall of approximately 550 mm [18]. During the research period, the average, minimum and maximum daily temperatures measured 1000 mm from the living wall were 18.7 °C, 2.6 °C and 45.6 °C, respectively, and the average air humidity was 64%. These measurements were recorded using a digital iButton hygrochron temperature/humidity logger (DS1923), which had a resolution of 0.5 °C, an accuracy of ±0.5 °C and a range of −10 °C to 65 °C [19].

2.1. Experimental Setup

The living wall comprised 144 Elmich Versiwall modular living wall pots, distributed evenly on 12 rows and 12 columns. The individual pots were 195 mm wide, 207 mm high and 192 mm deep, yielding a total volume of 1.8 L that contained 1.5 L of soil substrate. The living wall was fitted with a drip irrigation system comprising pressure-compensating drippers [20].

Two irrigation treatments were selected for this study, named *I1* and *I2*. Three substrate types were used: loam (L), native substrate (NS) and potting mix (PM). Six plant species were selected, namely, *Goodenia varia* (GV), *Einadia nutans* (EN), *Dichondra repens* (TT) *Dianella revoluta* (DR), *Myoporum parvifolium* (MP) and *Westringia fruticosa* (WF). There were 36 unique combinations of irrigation–substrate–plant, and each was replicated four times in the LW following a statistical design that included carry-over effects [20]. The full experimental design of the LW's plant–substrate–irrigation system is shown in Table 1.

Figure 2. Experimental Living Wall.

Table 1. Plant–substrate–irrigation arrangement on the living wall.

Row \ Column	1	2	3	4	5	6	7	8	9	10	11	12
12	EN-PM-I1	TT-PM-I1	WF-PM-I2	EN-L-I1	MP-NS-I2	DR-NS-I1	WF-L-I1	MP-L-I2	DR-L-I2	EN-L-I2	GV-PM-I1	DR-NS-I2
11	GV-NS-I2	GV-NS-I1	WF-NS-I2	MP-L-I1	WF-L-I2	WF-PM-I2	TT-L-I1	EN-NS-I1	DR-PM-I2	DR-L-I2	WF-PM-I1	DR-NS-I1
10	TT-PM-I2	GV-PM-I2	EN-PM-I2	DR-PM-I1	EN-L-I1	MP-L-I1	MP-NS-I1	WF-NS-I2	TT-L-I2	GV-L-I1	DR-NS-I2	GV-NS-I1
9	MP-NS-I2	EN-PM-I1	TT-L-I1	WF-L-I2	TT-NS-I1	GV-L-I2	MP-PM-I1	WF-L-I1	GV-PM-I2	EN-NS-I1	EN-L-I2	MP-L-I1
8	DR-NS-I1	WF-NS-I2	DR-L-I1	MP-NS-I1	GV-L-I2	EN-PM-I1	EN-NS-I2	DR-PM-I2	GV-L-I1	TT-PM-I2	GV-NS-I2	TT-PM-I1
7	MP-L-I2	EN-L-I1	GV-PM-I1	TT-NS-I2	EN-NS-I2	TT-PM-I1	WF-NS-I2	TT-PM-I2	MP-PM-I1	DR-PM-I2	DR-L-I1	EN-L-I2
6	MP-L-I1	DR-NS-I1	TT-NS-I2	GV-NS-I1	MP-PM-I1	DR-PM-I2	GV-NS-I2	GV-L-I2	MP-PM-I2	EN-L-I1	TT-L-I2	WF-PM-I1
5	EN-NS-I1	DR-L-I1	MP-PM-I2	DR-NS-I2	WF-PM-I1	DR-L-I2	GV-PM-I1	TT-NS-I1	EN-NS-I2	GV-PM-I2	MP-PM-I1	MP-L-I2
4	WF-NS-I1	TT-NS-I2	WF-L-I1	WF-PM-I1	DR-PM-I1	WF-L-I2	GV-L-I1	EN-PM-I2	EN-PM-I1	MP-NS-I2	TT-L-I1	GV-NS-I2

Table 1. *Cont.*

Row \ Column	1	2	3	4	5	6	7	8	9	10	11	12
3	WF-PM-I2	TT-L-I2	EN-NS-I1	TT-L-I1	MP-NS-I1	TT-PM-I2	MP-L-I2	WF-NS-I1	DR-L-I1	DR-PM-I1	MP-NS-I2	EN-NS-I2
2	DR-PM-I1	WF-L-I2	GV-L-I1	EN-PM-I2	MP-PM-I2	WF-NS-I1	WF-PM-I2	DR-L-I2	MP-NS-I1	TT-NS-I1	TT-NS-I2	GV-L-I2
1	EN-L-I2	DR-NS-I2	TT-L-I2	GV-PM-I2	GV-PM-I1	TT-NS-I1	EN-PM-I2	GV-NS-I1	WF-L-I1	WF-NS-I1	TT-PM-I1	MP-PM-I2

Note: plant species: DR: Dianella revoluta, EN: Einadia nutans, GV: Goodenia varia, MP: Myoporum parvifolium, TT: Dichondra repens, WF: Westringia fruticose; Soil substrate: L: organic sandy loam; NS: native soil; PM: potting mix; Irrigation: I1: Irrigation 1 (2 min @ 4 L/h); I2: Irrigation 2 (3 min @ 2 L/h).

2.2. Irrigation Application and ET Determination

For practicality, an automated irrigation system was established that was intended to deliver uniform irrigation volumes to all pots under two different irrigation regimes (*I1* and *I2*). Two irrigation volumes were employed on the drip irrigation system used, and the pots were irrigated daily, 2 min at 4 L/h for *I1* and 3 min @ 2 L/h for *I2*. The irrigation frequency was doubled in January and February whereby the plants were given their standard application twice a day at 7:00 am and at 5:00 pm, while the irrigation frequency was halved in winter (July and August), i.e., the standard application occurred once every 48 h. The extra irrigation in summer was significant to ensure that the plants would not be exposed to water stress. Meanwhile, the reduced irrigation in winter was driven by the cold and more humid weather.

Evapotranspiration was estimated from a daily water balance, according to [21], as shown in Equation (1). The water balance approach does not allow a differentiation between evaporation from soil and transpiration from leaves. Therefore, ET in this study represented the combined movement of water through soil evaporation and plant transpiration.

$$P + CR + Irr - ET - R - D \pm S = 0 \quad (1)$$

where P: amount of rainfall (mm/day), CR: capillary rise from the groundwater table (mm/day), Irr: irrigation dose (mm/day), ET: evapotranspiration (mm/day), R: runoff (mm/day), D: drainage (mm/day), S: storage of water in the soil compartment (mm/day).

As the plants in this experiment were in LW container pots, Equation (1) was modified to reflect the relevant parameters available in the LW pot for water balance. The LW was situated in an atrium area and, being vertical, only the pots on the top row were subjected to rainfall. Thus, rainfall (P) was not taken into account. The pot condition also nullified the groundwater and runoff effects. Drainage was measured as outlet drainage collected individually from each pot. The new water balance equation is shown in Equation (2).

$$Irr - ET - D \pm S = 0 \quad (2)$$

A correlation-based relationship was established between the ET rate calculated from each pot (based on soil moisture measurement, irrigation and drainage water balance) and the ET reported from a Davis Vantage Pro2 weather station installed in the atrium. This relationship was used to estimate the LW's ET based on observed weather conditions, thus allowing for the latent heat of vaporisation to be estimated throughout the entire experiment.

The LW pot by Elmich Versiwall has a small outlet at the bottom of the pot for drainage outflow. In this experiment, polyethylene tubing of diameter 7 mm was attached to each pot outlet, and this was connected to plastic bottles during the measurement of water drainage. Individual bottles were labelled, and their weight was taken. The weight of the outlet water captured was used to calculate the drainage outlet volume (D) in millilitres.

To account for the storage of water in the soil compartment (S in Equation (2)), the substrate moisture content was measured using a Vegetronix VH400 soil moisture sensor. Due to the different nature of the three substrates in this experiment, it was necessary to construct a relative substrate moisture curve for each substrate. These curves allowed the analysis to more accurately estimate the substrate water volume and subsequently estimate ET from the water balance.

The equipment was calibrated before use with each substrate. In the substrate moisture calibration, the substrates were oven-dried at 105 °C for at least 48 h to remove moisture. The substrates were examined for homogeneity in their size, and any large clumps were broken down. Next, the dry bulk density of each substrate was determined using Equation (3). The substrates were placed in a known container volume, and the mass of the substrates was recorded.

$$BD = \frac{m_{soil}}{V_{soil}} \tag{3}$$

where BD: dry bulk density in g/cm^3, m_{soil}: mass of substrate in g, V_{soil}: volume of substrate in cm^3

The dry substrates were transferred into containers tall enough to accommodate the length of the sensor. A known water mass (from 20 g up to 320 g) was mixed into the substrate. Moisture was evenly spread when added to the soil. The samples were placed in a temperature-controlled room. The measurement of voltage was taken from the soil moisture sensor at 0 h and 24 h. It was assumed that minimal evaporation occurred in the temperature-controlled room and that the moisture was thoroughly distributed in the sample at 24 h. All samples were prepared in triplicate.

Calibration equations for measured voltage against known volumetric water content (VWC) were derived for each substrate. The results for the substrate dry bulk density, the calibrated equations for substrate moisture content and their R^2 values are shown in Table 2.

Table 2. Bulk density and substrate VWC calibration equation.

Substrate	Bulk Density (g/cm^3)	Voltage vs. VWC Calibration	R^2
Loam (L)	1.411	y = 17.163 x − 16.871	0.968
Native soil (NS)	1.345	y = 21.442 x − 16.195	0.745
Potting mix (PM)	0.470	y = 25.838 x + 2.4266	0.950

Note: VWC: Volumetric water content.

These calibration equations were used to determine the substrate moisture content and subsequently, in the water balance, Equation (2), to determine the ET rate. Measurements on the LW were conducted when there was no rainfall. Initially, the VWC reading for individual pots was recorded using a Vegetronix VH400 before irrigating the plants with a known irrigation volume. After irrigation, the containers collecting outlet water were left for at least 20 h to allow all drainage water to flow through the substrate. On the following day, the VWC readings of the individual pots were again recorded, along with the weight of drained water through the outlet from the previous experiment.

2.3. Latent Heat of Vaporisation

Water leaving the LW through ET, as calculated using Equation (2), was expected to be vaporised into the air, hence providing cooling to the microclimate. The energy flux involved in this process can be quantified using the concept of the latent heat of vaporisation. The latent heat of vaporisation is the heat energy required to change liquid water to gas (water vapour).

The ET from the plants was measured using an irrigation and drainage water balance. The measured ET was used to calibrate the reference ET obtained daily from the weather station installed within the same atrium. The hourly ET from the weather station was estimated using the air temperature, relative humidity, average wind speed and solar radiation data [22].

A relationship between the calculated ET and the inferred ET from the weather station was established. From the relative ET rate of the LW plants, the latent heat of vaporisation was calculated using Equation (4).

$$Q = m \times L \quad (4)$$

where Q: heat energy absorbed (kJ), m: mass of the substance (kg), L: specific latent heat of the substance (kJ/kg). The specific latent heat, L, of water is 2260 kJ/kg [23].

January 2018 was chosen because it was the month with the highest ET once the LW plants had been established. Moreover, according to a previous energy balance analysis of living walls, ET accounts for more than 50% of heat released in summer, while ET in winter is often very small [24].

3. Results and Discussion

3.1. Water Balance

An experiment to quantify the outlet water volume and the change in substrate moisture was conducted to determine the water volume and ET for each LW pot. The maximum ET rate (minimum drainage volume) was chosen to eliminate irregularities due to irrigation distributions. A correlation was established between the ET recorded by the weather station and the maximum ET for each pot. Finally, the maximum ET rate for each unique combination treatment was selected as the relative ET. With the correlation established, the ongoing automatic measurement of ET from the weather station was used to estimate the daily ET from each pot.

An experimental issue encountered was that occasionally the irrigation lines emptied their water through the drip emitters after the irrigation was switched off. To minimise the effects of this, the final ET was used only if: (1) the change in storage of water, S, in the substrate was within 10% between two consecutive measurement days; and (2) less than 20% of the scheduled irrigated water volume was collected as drainage. If these two conditions were met, it was deemed reasonable to expect that the pot did not receive additional water from the emptying of the irrigation pipe. Table 3 shows the observed ET values in mL of water transpired per mm of potential ET recorded by the weather station. No correlation could be established for DR in Loam for *I1*, as the four treatments on the LW did not meet the above two set criteria.

Table 3. Average relative ET rate for plant–substrate–irrigation treatments with ET from the weather station, in mL per mm of ET per pot.

Substrate Plant Species	L		NS		PM	
	I1	**I2**	**I1**	**I2**	**I1**	**I2**
DR	N/A	49.7	63.7	59.5	76.6	54.4
EN	91.9	43.7	79.0	51.1	74.0	41.0
GV	54.0	43.0	72.6	50.2	54.5	52.4
MP	71.5	51.9	81.1	53.2	70.0	52.3
TT	54.7	45.0	58.2	54.4	46.7	48.3
WF	60.8	67.5	66.3	48.1	62.5	41.2

Note: DR: Dianella revoluta, EN: Einadia nutans, GV: Goodenia varia, MP: Myoporum parvifolium, TT: Dichondra repens, WF: Westringia fruticosa, L: Loam, NS: Native soil, PM: Potting mix, I1: irrigation 1, I2: irrigation 2, N/A: data not available.

The results indicated that the range of ET from the LW experiment varied by a factor of 2, from 41 to approximately 90 mL/mm of ET per LW pot. These are high values compared to those in the only previous study [13] that measured ET from a complete water balance on a living wall. In that previous study, the range of relative ET was 0.7 to 1.07 mL/mm, but this was measured in the cold and wet winter months of November and December in the Netherlands. In addition, the two living walls that were instrumented in that study were quite small (0.33 and 0.67 m^2).

3.2. Latent Heat of Vaporisation

The derived ET from the weather station (from Table 3) was applied to Equation (4) to estimate the latent heat of vaporisation of the various LW plants. The LW consisted of 144 pots with an area of 7.2 m^2, which equates to 20 pots per m^2. Only cooling was considered, and the calculations for the minimum and maximum latent heat of vaporisation were made for January 2018, using the minimum (41.0 mL/mm of ET per pot) and maximum relative ET (91.9 mL/mm of ET per pot), respectively, as shown below:

ET rate for January 2018 from the weather station	=92.3 mm/month
Minimum ET calculation:	
Relative ET rate (minimum)	=41.0 mL/mm of ET per pot
Minimum ET per LW pot	=41.0 mL/mm × 92.3 mm/month =3784.3 mL/month per pot
Minimum ET rate per m^2	=3784.3 mL/month per pot × 20 LW pots/m^2 =75.7 L/month/m^2
Minimum latent heat of vaporisation per m^2 from Equation (4).	=75.7 × 2260 kJ/month/m^2 =171 MJ/month/m^2
Maximum ET calculation:	
Relative ET rate (maximum)	=91.9 mL/mm of ET per pot
Maximum ET per LW pot:	=91.9 mL/mm × 92.3 mm/month =8482.4 mL/month per pot
Maximum ET rate per m^2	=8482.4 mL/month per pot × 20 LW pots/m^2 =169.6 L/month/m^2
Maximum latent heat of vaporisation per m^2 from Equation (4).	=169.6 × 2260 kJ/month/m^2 =383 MJ/month/m^2

The range of the calculated latent heat of vaporisation values for the LW was therefore from 171 to 383 MJ/month/m^2 for the month of January 2018. For comparison, the range of the latent heat of vaporisation values reported by He et al. [24] was lower, from 6 to 64 MJ/month/m^2. However, this was estimated through heat measurements using a model. It also involved temperature measurements through the brick wall on which the living wall was mounted, which would provide additional insulation that would greatly reduce the overall heat flux.

To understand how much of a cooling effect the heat flux in the current study signified, it was interesting to compare these values against the performance of an alternative, commonly used WSUD technology, namely, porous pavements. In an outdoor porous concrete pavement installation, Li et al. [15] estimated the evaporative cooling as the measured latent heat flux, which in their study over several days averaged around 190 W/m^2. In an experimental study, Yang et al. [16] examined how evaporation from porous pavement systems can affect the surrounding environment, particularly in terms of air temperature. They defined evaporative cooling as the measured latent heat flux, which in their experiments ranged from 27 to 240 W/m^2. While this equates to a range from 71 to 641 MJ/month/m^2, Yang et al. [16] stated that this evaporative cooling effect only occurred when water was available in the upper 13 mm of the porous concrete pavement. This water availability would only occur after rainfall and, due to the high permeability of porous concrete, on dry days there would be no water in the porous concrete system and hence no cooling effect.

The month of January in Adelaide has a long-term median rainfall of 19.6 mm but only a mean number of days of rain (≥1 mm) equal to 2.9 [18]. This means that in the month of January in Adelaide, a porous pavement system would have an evaporative cooling effect in the range of:

$$\frac{2.9}{31} \times 71 \ to \ \frac{2.9}{31} \times 641 \text{ MJ/month/m}^2$$

This equates to a range from 7 to 60 MJ/month/m^2, which is 4 to 15% of the range from 171 to 383 MJ/month/m^2 for the LW that was estimated in this study. This finding is not surprising for two reasons. The first is that porous concrete can only cool through an evaporative process. Secondly, because of its vegetation, an LW can transpire for long periods after rainfall, partly because of the water that is added to the system through irrigation, which is absent in a porous pavement system. Therefore, for the month of January in Adelaide, it is clear that a vegetative wall would have a greater cooling effect than an equivalent porous pavement system. However, further research is required to ascertain whether this benefit would be replicated over an entire annual cycle.

4. Conclusions

This study investigated the cooling potential of a 144-pot experimental living wall located in a temperate Mediterranean climate in Adelaide, South Australia. The experimental design consisted of 36 combinations of irrigation–substrate–plant, with each being replicated four times. The range of the measured evapotranspiration rates from the living wall varied by a factor of 2, from 41 to approximately 90 mL/mm per pot. The range of the calculated latent heat of vaporisation values for the living wall was from 171 to 383 MJ/month/m^2 for the month of January 2018. These values were compared against the cooling performance of an alternative WSUD technology, namely, porous pavements. It was found that an equivalent porous concrete pavement would only have 4 to 15% of the evaporative cooling effect that was measured for the experimental living wall. A minor limitation of this study is the reliance on calibration equations for estimating the volumetric water content for each substrate. While the resulting R^2 values were high, improvements in the estimates are always possible. A further limitation is the estimation of irrigated water, due to the irrigation lines emptying their water through the drip emitters after the irrigation was switched off. Steps were taken to minimize this effect, but an improved irrigation system should perhaps be considered for future studies. Future research would also be useful to extend the estimation of the cooling effects to months that are less hot than January. This could be achieved either experimentally, as in this study, or using a modelling technique.

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