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Land surface temperature and soil moisture distribution characteristics for a raingarden in Fitzroy Gardens, Melbourne

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Abstract: To better understand the cooling effect of a raingarden in Fitzroy Gardens, Melbourne, as well as its benefits for an urban microclimate, two rounds of 36-h microclimate monitoring at the raingarden were conducted. Land surface temperature and soil moisture were analyzed according to monitoring data. The results show a clear raingarden cooling effect in summer. The largest difference of land surface temperatures inside and outside the raingarden can reach 23.6 ℃, and the diurnal variation in temperature inside the raingarden was much less than that outside the raingarden. The soil moisture increased rapidly after irrigation, with the increase in the volumetric water content (VWC) of 2% to 3.6%. The soil moistures of adjacent irrigated garden beds and grass were higher than those inside the raingarden. Monitoring soil moisture helps guide raingarden irrigation.

Key words: raingarden; microclimate; land surface temperature; soil moisture

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Humans need a comfortable climate to survive. The scale of climate most suitable for human living is called the microclimate-climate during a 24-h period, space within a width from 100 m to 1 km in a horizontal dimension, and below 100 m in height[1]. Urban environments are warmer than their rural surrounds. Consolidation processes that are evident worldwide and that are driven by the need to reduce encroachment on rural land and to increase transport, energy and carbon efficiency, threaten to further increase urban temperatures[2]. The combination of excessive heating driven by urban development, low water availability and future climate change impacts can compromise human health and amenities for urban dwellers.

The concepts regarding urban water include a sustainable urban drainage system in Britain, low impact development in USA[3], water sensitive urban design in Australia[4–5], as well as sponge cities in China[6].

A review of the literature has identified that there is a possibility to intentionally modify urban climates by reintegrating stormwater back into the urban landscape through sponge cities, such as strengthening infiltration and irrigation by rainwater. These approaches are effective in restoring natural hydrological conditions via increasing soil moisture and evapotranspiration, providing more water for vegetation and a green infrastructure. Therefore, sponge cities are expected to decrease environmental temperatures and reduce human exposure to heat. However, the urban climate benefit (the intensity of cooling and improvement of human thermal comfort) greatly depends on a multitude of factors including local environmental conditions, the design and placement of sponge cities, and the nature of the surrounding urban landscape.

Two 36-h microclimate-monitoring rounds were undertaken in a raingarden in Fitzroy Gardens, Melbourne, to gather more empirical evidence demonstrating the climatic benefits of sponge cities. The study can lead to a better understanding of the extent to which watering such systems before and during heat wave days can be effective in urban heat mitigation. The results will also help us develop a water budget (through time series simulation) for the municipal department specifically aiming at a heat mitigation strategy through pre-emptive watering of raingardens and other similar vegetated areas.

1 Related Work

Microclimate research in new concepts of water cities similar to sponge cities has been conducted in the Corporative Research Center for Water Sensitive Cities, Australia. Researchers reviewed urban water and energy budgets, and identified that water sensitive urban design (WSUD) has the potential to provide cooling effects across the urban landscape through both evapotranspiration and shading. By analyzing the thermal benefits of urban road trees and green roofs[7–8], it revealed that irrigation plays a crucial role in urban environment cooling.

The traditional stormwater infrastructure (i. e. drainage) rapidly exports stormwater away from the urban environment and results in dry urban landscapes. The hypothesis is that sponge cities can reintegrate stormwater back into the urban landscape, which helps to restore the water balance and influence the urban climate by modifying the urban radiation budget and surface energy bal-

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ance[9]. This in turn drives the environmental parameters that influence human thermal comfort. While this sounds promising theoretically, there is limited empirical evidence supporting the climatic benefits of sponge cities. The scale of interest focuses primarily at the micro scale, a scale of implementation of sponge cities and people's lives. Given the growing support for sponge cities, it is important to assess the additional benefits for extreme heat events and UHI mitigation from increased water availability, and to provide insight into how to maximize these benefits through architecture and landscape planning.

Urban energy and water balances are connected through evapotranspiration[10]. Evapotranspiration can directly modify the urban water balance and energy balance, which is a fundamental controller of urban climates. Hence, there is a potential for modifying evapotranspiration to control the urban climate. The urban energy balance for a surface layer urban volume is given by

$$Q^{*} + Q_{F} = Q_{H} + Q_{E} + \Delta Q_{S} + \Delta Q_{A} \tag{1}$$

where Q^{*} is the net all-wave radiation (solar and terrestrial radiation); Q_F is the anthropogenic heat flux; Q_H is the sensible heat flux (atmospheric heating); Q_E is the latent heat flux (or evapotranspiration); ΔQ_S is the net storage heat flux; and ΔQ_A is the net horizontal advective heat flux[11], W/m^2.

The urban water balance is given by

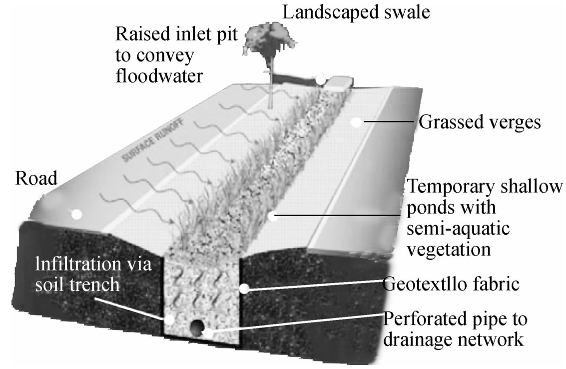
$$P + I = E + D + \Delta S \tag{2}$$

where P is the precipitation; I is the piped water supply; E is the evapotranspiration; D is the drainage (stormwater and wastewater); and ΔS is the change in water storage[12], mm/h. Hence, the connecting component is evapotranspiration since Q_E, the latent heat flux, is the heat released through evapotranspiration.

Sponge cities have the potential to provide cooling effects across the urban landscape through increasing evapotranspiration and shading. It is possible to cool cities efficiently through harvesting rainwater to support the green infrastructure in the urban landscape through sponge cities' design (green roof, bioretention etc.).

Microclimate benefits of sponge cities are related to the specific application and sites. Simply increasing vegetation and irrigation, without considering actual conditions, will not create much benefit for microclimate improvement. The cooling effect not only depends on wind speed and the dominant wind direction, but also on the surrounding buildings and layout[13]. The downwind cooling effects will be weakened by buildings. Building environments are crucial in design for climate adaptation. To maximize climate benefits, sponge cities should be fit-for-place, servicing heat-sensitive environments including natural and artificial landscapes[14].

Raingardens are part of the family of stormwater biofiltration systems or biofilters and bioretention systems. A typical biofiltration system consists of a vegetated swale or basin overlaying a porous filter medium (usually soil-based) with a drainage pipe at the bottom. Fig. 1(a) is the principal sketch of a typical raingarden[15], and Fig. 1(b) is a photo of a typical raingarden, which was taken by author, in Darling Street, East Melbourne. Small bioretention pods are often referred to as raingardens, while larger systems with grooves are called bioretention basins or swales[8,15].



(a)

(b)

Fig. 1 Typical raingarden. (a) The sketch[15]; (b) The Photo

Urban drainage infrastructure is generally designed to rapidly export stormwater away from the urban environment to minimize flood risk created by extensive impervious surface cover.

However, cities and towns at times face water restrictions in response to drought and water scarcity. This can exacerbate heating and drying, and promote the development of unfavorable urban climates.

However, sponge cities usually accelerate soil infiltration rates which dry soil quickly after rain, leading to a soil moisture too low to cool cities. Thus, it should be researched how sponge cities improve urban climate to realize the dual goals of urban water balance and cooling cities.

2 Method

2.1 Investigation for monitoring site

An investigation of raingardens in Melbourne was conducted on Nov. 2014 in order to choose a proper site for microclimate monitoring (see Fig. 2). The raingarden in Fitzroy Gardens is selected for facilitating gear set-up and irrigation.

Raingardens support fast infiltration. Soil in raingardens always fluctuates greatly between wet and dry conditions, which is not ideal for plant growth, and might even be detrimental for plant health. Raingardens' soil should be between saturation point and wilting point to make sure that plants can have sufficient but not too much water[16]. Soil moisture monitoring is necessary to inform proper raingarden irrigation.

Fig. 2 Raingarden in Fitzroy Gardens, Melbourne

2.2 Monitoring equipment set-up

This monitoring is undertaken to evaluate the climate cooling performance of the large raingarden (253 m^2) that has been installed at the southern end of Fitzroy Gardens, Melbourne (near the intersection of Jolimont Rd and Wellington Parade).

The meteorological equipment is stand-alone, battery-powered and required no modification to the existing infrastructure. The monitoring gear set-up is as shown in a plan view in Fig. 3. There were two rounds of monitoring. One was from 11:30 on 2015-02-06 to 18:25 on 2015-02-07, and the other was from 07:55 on 2015-02-21 to 16:40 on 2015-02-22.

Fig. 3 Plan view of Fitzroy Raingarden microclimate observation gear

Fig. 3 shows the pole arrangement. Six poles of 3 m in length were installed inside and adjacent to the raingarden, along the axis of the wind direction (northwest-southeast), each with an automatic weather station. Fig. 4 shows a cross section of the poles, P stands for Pole.

Six automatic climate stations were designed respectively according to the monitoring objectives to be installed on six poles. Poles 1, 2, 4 and 6 are installed 4 HMP45AC (Vaisala) sensors within 4 Gill shields for air temperature and relative humidity at a height above the surface of 0.3, 0.75, 1.5 and 3 m (see Fig. 4); and data was collected every second and the average value of every 5 min was logged on a CR1000 control data logger

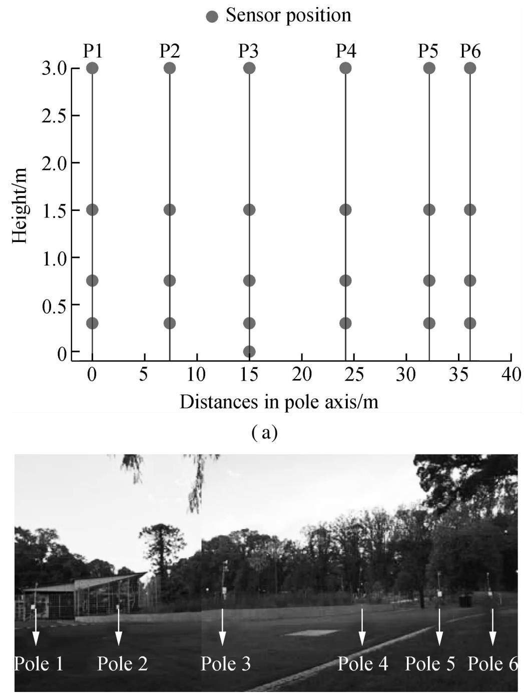


Fig. 4 Masts installed at raingarden. (a) The cross section; (b) The Panorama

(Campbell Scientific). Pole 3 has five HMP45AC sensors with the extra sensor mounted immediately above the surface. Pole 3 is also installed with an infrared temperature sensor (SI-121, Apogee) for providing outgoing long wave radiation and a derived surface temperature; and a CNR1net radiometer (Kipp&Zonen) for the analysis of the radiation balance of solar and far infrared radiation. These two radiation sensors were installed on the top of Pole 3. This set of measurements was used to estimate the net radiation Q^* near the surface.

Pole 3 has a wind monitor (R. M. Young Model 05103) for monitoring wind direction and wind speed on the top and a wind speed sensor 014A (Met One Instruments, Inc) at 0.3 m above the surface of the raingarden inside. Data from Pole 3 were recorded on a CR5000 logger (Campbell Scientific) every 5 min. Pole 5 has four wind speed sensors 014A (Met One Instruments, Inc) at the same height as the 4 HMP45AC sensors, which are the same as Poles 1, 2, 4 and 6. We also installed a IRTS sensor (SI-121, Apogee) on the top of Pole 5 to measure the road surface temperature outside the raingarden. The data for Pole 5 were logged every 5 min on a CR3000 logger (Campbell Scientific). Poles 1, 5 and 6 were placed outside the raingarden, Pole 1 was upwind and Poles 5 and 6 were downwind. Poles 2, 3, and 4 were in the raingarden. The distance between Poles 2 and 3 is 7.6 m and the one between Poles 3 and 4 is 9.2 m.

Hydrosense Ⅱ (Campbell Scientific) with CS658 sensors were employed for soil moisture measurement, as well as the OS425-LS non-contact infrared thermometer. A top-end IR Thermographic Camera ThermoPro TP8 (Guide) was also employed for the land surface temperature. These measurements were taken every 3 h between 17:00 and 08:00 the next morning during monitoring. The soil moisture monitoring points were at Poles 2, 3 and 4 inside the raingarden and in the regular garden bed grass outside the raingarden in order to understand soil moisture changes among different soil types/land uses. The land surface temperature points are at Poles 1, 2, 3, 4, 5, the mix of gravel, bricks and pavements (gravel, bricks & pavements, G & B & P, shown in Fig. 3), and the mix of garden and grass (garden & grass, G & G, shown in Fig. 3) outside the raingarden. The ThermoPro TP8 (Guide) was used to compare the surface temperatures of various surfaces and to obtain visible and thermographic images.

The following discussion concerns only the soil moisture and land surface temperature distributions in and outside the raingarden in Fitzroy Gardens.

3 Results

3.1 Land surface temperature of the raingarden in Fitzroy Gardens

The land surface temperature at 10:00, 14:00 and 17:00 on 2015-02-21 were chosen to show the cooling effect of the raingarden. Tab. 1 provides the surface characteristics and average temperature for each point.

Tab. 1 Land surface temperature of measured points on 2015-02-21 and surface characteristics of measured points ℃

Measured time	Pole 1 (pavements)	Pole 2 (inside raingarden)	Pole 3 (inside raingarden)	Pole 4 (inside raingarden)	Pole 5 (outside raingarden)	G & B & P (gravel, bricks and pavements)	G & G (garden and grass)
10:00	31.8	26.7	29.5	26.1	30.4	38.3	31.8
14:00	58.0	43.3	39.2	38.7	53.3	59.3	40.9
17:00	35.3	28.4	27.2	26.9	30.8	34.5	30.9

The land surface temperature of gravel and bricks and pavements was the highest among the seven different points. The downwind cooling effect made P4 the lowest temperature among the three points inside the raingarden (P2, P3 and P4). Due to the raingarden cooling effect, the three points inside all had temperatures lower than the four points outside: P1, P5, G & B & P, G & G.

The temperature difference between the highest and lowest reaches 20.6 ℃ at 14:00 at the time of maximum solar radiation, 12.2 ℃ at 10:00 and 8.4 ℃ at 17:00. Even at 17:00 after rain, it is clear that it is cooler inside the raingarden than outside, indicating a strong cooling effect of raingarden.

The mechanism of the raingarden cooling effect can be explained by Fig. 5[9], which presents the generalization of key processes in the formation of urban microclimates during summer for conventional (water limited) urban landscapes (Figs. 5(a) and (c)) and sponge city urban landscapes (Figs. 5(b) and (d)) for day and night conditions. The raingarden is a typical kind of sponge city urban landscape. In Fig. 5[9], surface radiation and energy balance processes are presented with arrows denoting direction and relative strength of the fluxes. The relative level of human thermal comfort experienced in each case is shown by the human and by the corresponding human thermal comfort (HTC) scale. In the conventional urban landscape during the day, a combination of high sensible heat flux and strong radiative heat load results in a hotter environment for urban dwellers. In contrast, the water sensitive landscape provides higher water availability to soils and waterways, along with healthy, full canopied vegetation, compared to the conventional water limited, xeric urban landscape. Sponge city increases evapotranspiration and shading, and reduces surface temperatures, radiative and heating loads. These result in improving human thermal comfort. Reduced heat storage during the day is beneficial at night, as less energy is available to support ongoing low-level atmospheric warming. Cooler

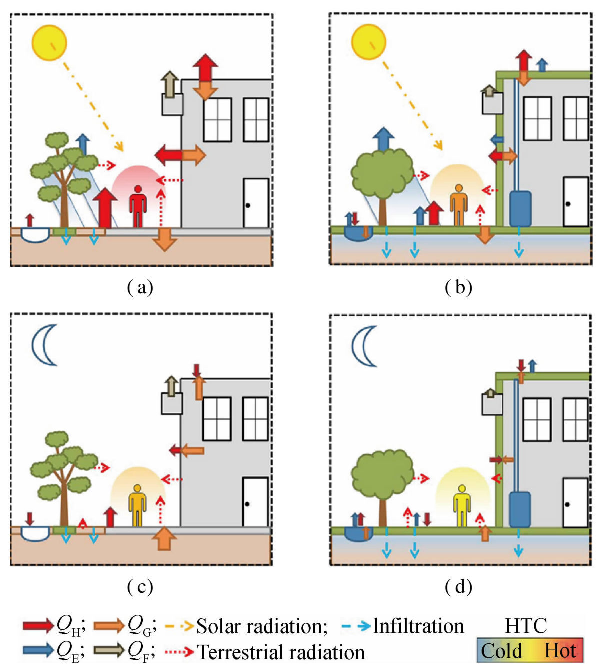


Fig. 5 Generalization of key processes in the formation of urban microclimates during summer. (a) For conventional (water limited) cities in the daytime; (b) For sponge cities in the daytime; (c) For conventional (water limited) cities during the night; (d) For sponge cities during the night[9]

outdoor environments along with reduced heat transfer into buildings limits the need for indoor air conditioning and associated anthropogenic heating. Other factors may also be influential, but are not presented here, such as air pollution effects on radiation and wind flows.

3.2 Temporal Variation of Temperature in Fitzroy Gardens' Raingarden

Fig. 6 shows the diurnal (time) variations of land surface temperature measured by the IRTS sensor on Pole 3 (in the middle of the raingarden) and on Pole 5 (outside the raingarden). Fig. 7 is the net irradiance plot obtained using the CNR1 sensor on Pole 3. The two figures above both show raingarden filling times (blue dotted line), lasting 20 min each time; and the adjacent lawn irrigation start time (pink dotted line), each irrigation lasting 20 min also. The rainfall incident happened during the second monitoring, between 16:00 and 17:00 on 2015-02-21. There was regular irrigation during the first round monitoring while the precipitation event occurred only once in the second round of monitoring. The biofilter (raingarden) filling occurred within the raingarden and the lawn irrigation outside the raingarden. Therefore, the focus was on the land surface temperature change on Pole 3 before and after the filling, together with the change since and after the lawn irrigation on Pole 5.

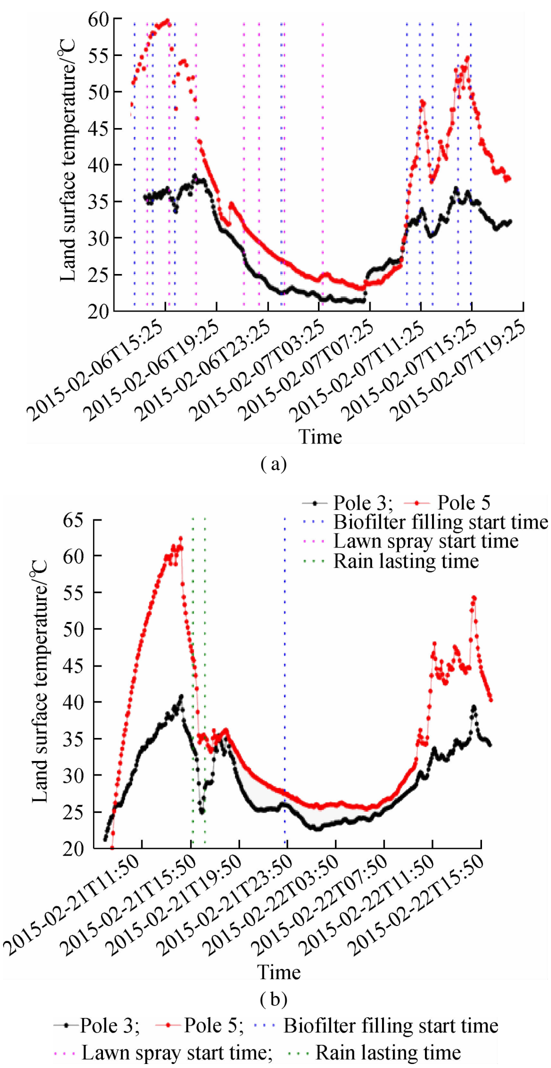


Fig. 6 Land surface temperature measured by IRTS sensors on Pole 3 and Pole 5 over two monitoring periods. (a) The first monitoring round; (b) The second monitoring round

The sudden drop of land surface temperature after irrigation (more apparent on Pole 3 profile) was the result of a sharp change in surface energy balance. Land surface temperature change is a response to the change in energy and water balance (evaporative cooling mainly), and this also drives air temperature change since there is less sensible heating above the surface.

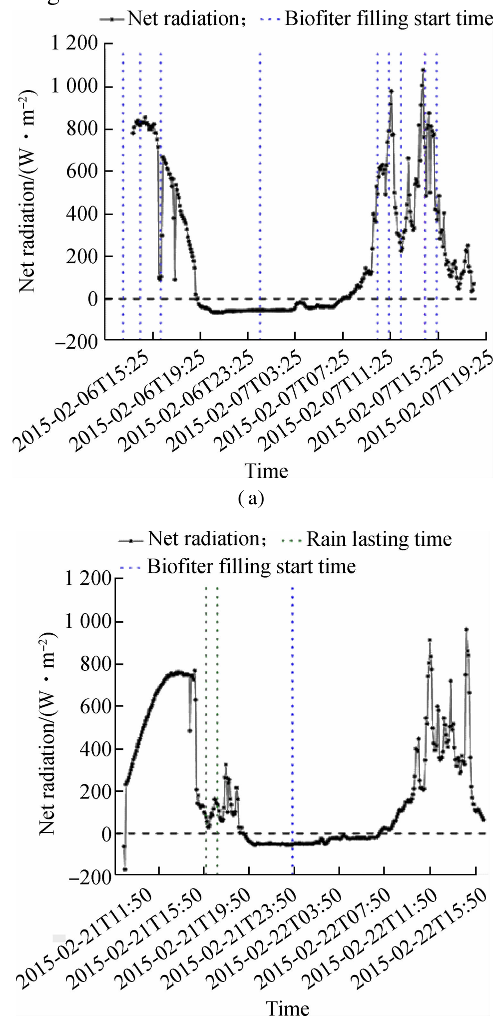


Fig. 7 Net radiation from CNR1 sensor on Pole 3 in the middle of the raingarden over two monitoring periods. (a) The first monitoring round; (b) The second monitoring round

The land surface temperature profile shows that there was a drop in land surface temperature on Pole 3 in the middle of the raingarden after irrigation. It also ocurred on Pole 5 outside the raingarden. It is not unexpected that the sudden decrease of land surface temperature was particularly apparent in the afternoon when it was relatively hot. Irrigation has the effect of cooling down the land surface temperature[17]. Moreover, from the air temperature dependency on surface temperature, it is clear that the air temperature also came down after irrigation.

The difference in land surface temperature between Poles 3 and 5 is also worthy of discussion. Fig. 6 demonstrates that the land surface temperature inside the raingarden is much lower than outside. The largest temperature difference was 23.6 ℃ at 15:05 on 2015-02-06, and it came down to 18.6 ℃ at 14:40 on 2015-02-07. The largest temperature difference was 22.7 ℃ on 2015-02-21 at 14:20 while on 2015-02-22 it was 15.0 ℃ at 15:20. Clearly, during the hot hours in the afternoon, the raingarden has a marked cooling effect.

The land surface temperature trace of Pole 5 in the second monitoring session was similar to that of net radiation from CNR1 on Pole 3. However, the trace of Pole 3 seems gentler than that of Pole 5, but it still followed the curves of radiation.

The land surface temperature curve of Pole 3 was a reduced mirror image of Pole 5. This might be due to the location of Pole 3, which was in the middle of the raingarden. The raingarden with moist soil and plants is partitioning much of the incoming solar radiation into evaporative heat, rather than heating the surface and atmosphere. This makes the land surface temperature change much more slowly than at Pole 5. Pole 5 was also set in the garden as shown in Fig. 8. However, the sensor was pointed towards the asphalt road.

Fig. 8 The image of Pole 5

The increase in cloud during the afternoon of the second monitoring period was likely responsible for the sharp drop in surface temperature, particularly at Pole 5 around 15:00 in the afternoon. There was also a sharp decrease of land surface temperature around 16:00 to 17:00 on 2015-02-21, particularly at Pole 3. This is mainly caused by the precipitation from 16:00 to 17:00 on 2015-02-21 which is shown as a green dotted line in the plots.

3.3 Soil moisture inside and outside the raingarden in Fitzroy Gardens

The soil moisture in and around the raingarden in Fitzroy Gardens measured by the Hydrosense Ⅱ (Campbell Scientific) was manually recorded. Measurements were taken hourly from 10:00 to 18:00 on 2015-02-07, and from 9:00 on 2015-02-21 to 16:00 on 2015-02-22, except every 3 h between 20:00 on 2015-02-21 and 8:00 on 2015-02-22. Since there were only five points of the volume water content (VWC) on 2015-02-07, only plots of VWC between 2015-02-21 and 2015-02-22 were provided (see Fig. 9).

The soil moisture rose as a result of rain and biofilter (raingarden) filling. The garden had a higher VWC than grass and soil moisture at these two sites was much higher than that within the raingarden (Pole 3, Pole 4 and Pole 2). The VWC increased right after rain by 4.8 % for Pole 3, 4.7% for Pole 4, 2.3% for Garden and 3.8% for Grass. Similarly, after biofilter (raingarden) filling,

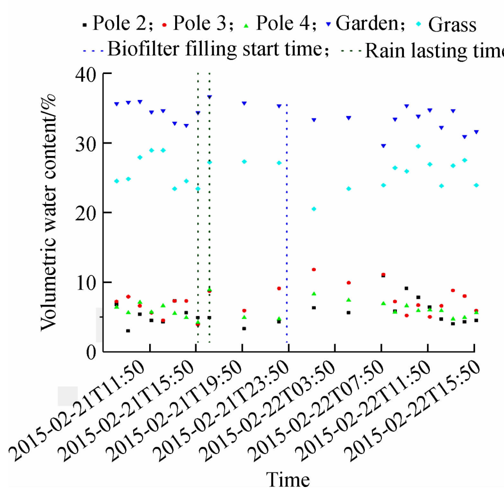


Fig. 9 Soil moisture volumetric water content in the raingarden between 2015-02-21 and 2015-02-22

which occurred only in the raingarden, the increases were 2% for Pole 2, 2.7% for Pole 3, 3.6% for Pole 4, while the VWC in the two spots of the garden and grass decreased by 2% and 6.6%, respectively, due to evapotranspiration. The raingarden clearly supports fast infiltration as a result of the highly porous media used in the raingarden. Soils will dry quickly after rain or biofilter (raingarden) filling. Thus, soil moisture in the raingarden was found to be lower than outside.

The increase of soil moisture after rain coincided with the land surface temperature decrease after rain as shown in Fig. 9. Soil moisture is regarded as an indicator to know when and how to irrigate. While increasing soil moisture may support surface cooling during the day, higher soil water content can actually serve to increase the heat capacity of soils. On the other hand, at night, high moisture soils may not cool as rapidly as dry soils.

4 Conclusions

1) The investigated raingarden shows a remarkable cooling effect. It is cooler in the raingarden than outside. The largest temperature difference can reach 23.6 ℃, while even the smallest gap is 8.4 ℃. The downwind space around the raingarden should be a cooler space as a consequence. The land surface temperature in the downwind area decreases, mainly due to downwind cooling. The land surface temperature of gravel, bricks and pavements (G & B & P) is the highest among the seven surfaces.

2) The land surface temperature change is the result of the change in energy and water budgets. This is why air temperature changes as well. The land surface temperature profile shows that land surface temperature goes down after irrigation. The land surface temperature plot has a similar trend to the net radiance plot. This is because energy change is the cause of land surface temperature change. The plots of land surface temperature change modestly compared with outside due to the moist soil and vegetation in the raingarden. Soil and vegetation partition most energy into evapotranspiration, buffering the land

surface temperature change.

3) The raingarden supports fast infiltration. The soil dries quickly after rain. Thus, soil moisture in the garden and grass is higher than in the raingarden. The increase of soil moisture after irrigation and/or rain occurs rapidly. After one rainfall event, the soil moisture increases by 4.8%, higher than the increase of soil moisture outside the raingarden. Soil moisture in the raingarden should be maintained between the saturation point and wilting point to ensure that vegetation can have sufficient water. Soil moisture monitoring is required in order to guide raingarden irrigation.

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墨尔本 Fitzroy 公园雨水花园地表温度与土壤湿度分布特征

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摘要：为了解墨尔本 Fitzroy 公园的雨水花园在夏季里的降温情况，以期为海绵城市改善城市微气候的研究提供数据支持，记录了 2 次连续 36 h 微气候观测过程，根据观测数据进行了地表温度与土壤湿度的分析. 结果表明：雨水花园在夏季有明显的降温作用，雨水花园地表温度内外差值最大达到 23.6 ℃，内部温度变化缓于雨水花园外的地表温度变化；灌溉后土壤湿度迅速提升，体积含水量（VWC）上升幅度在 2% ~3.6%；花园与草地等绿地土壤湿度高于雨水花园内部土壤湿度；监测土壤湿度有利于指导雨水花园的灌溉方式.

关键词：雨水花园；微气候；地表温度；土壤湿度

中图分类号：P463.3