



# Field monitoring and assessment of the impact of a large eucalypt on soil desiccation

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## Abstract

Expansive soils, or reactive soils, experience moisture changes under the prevailing climate conditions, leading to shrink during dry periods and swell in wet months. Houses founded on such problematic soils are subjected to considerable ground surface movements, which can greatly affect the function and performance of buildings. Such movements will increase with the presence of a tree or tree groups nearby since tree roots can extract considerable amounts of water from soils, resulting in localized shrinkage settlement. In this study, a field site was selected with a large native spotted gum tree in a well-established eastern suburb of Melbourne, Victoria. The site and tree are fully instrumented. Surface and sub-surface movement pads, in situ soil psychrometers and neutron moisture meter access holes were installed to evaluate soil moisture/suction changes and subsequent ground movements. A sap flow meter that incorporated the heat ratio method was installed on the north side of the main trunk of the tree at breast height to enable sap velocity and sap flow volume to be closely monitored. Soil types, degree of reactivity and capability of soil water retention have been evaluated through a number of laboratory soil tests including shrink-swells, Atterberg limits, and soil water characteristic curve determination. This paper presents the preliminary monitoring results for a period of 6 months. Valuable field data such as this can help geotechnical engineers and practitioners to get a better understanding of the physical processes that drive tree root-expansive soil interaction and in time improve the current footing design guidelines.

**Keywords** Ground movement · Expansive soil · Sap flow · Soil suction · Spotted gum tree

## 1 Introduction

Trees are major urban infrastructure assets to our environment and our society [23]. A wide variety of tree species are present in the urban environments, which add to national greening in densely populated cities and rural areas, reducing greenhouse gas emissions (GHGs) and providing visual appeal to any area. Trees can significantly

enhance the design of a streetscape. Trees, however, exert negative water potential on foundation soils, which may cause unacceptable distortions and cracking of light-weight structures supported on these soils [17].

Tree root architecture has been of considerable interest to horticulturists and now engineers. Yeagher [33] found that soil moisture availability has a significant influence on the extent of the tree root system. Due to the physical limitations of tree roots, they will extend their roots as far as they must in order to survive or proliferate. According to Fityus et al. [13], the extent of tree roots may be relatively small if sufficient water is available; however, if soil water is restricted, roots have to extend to a greater depth to avoid high suction levels developed seasonally in near-surface soil, and/or extend many metres laterally. Mercer et al. [32] discussed potential root development both laterally and with depth and recognized that root architecture depends upon the environment, water and oxygen availability, and the ability of the genus to proliferate roots when under

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water stress. In Australia, Cameron [7] observed that the drying influence of tree roots on soil could extend to depths of 3–5 m in the dry season. For tree groups (three or more), Cameron surmised that tree root systems can extract water from at least 6 m to compete with neighbouring trees [8].

Tree proximity rules are not new, e.g. Ward [31]. In the UK, guidelines on species and safe proximity have been published for low-rise residential buildings founded on clay soils by the National House Building Council (NHBC) [24]. Much of the research work behind the NHBC has been carried out in southeast England where there are clays with high reactivity (e.g. Cutler and Richardson [9, 10], Biddle [2–4], Mercer et al. [32], Driscoll and Skinner [11]). The NHBC guidelines are based on firstly the plasticity index of the soil modified for the percentage of soil particles in excess of 425 microns, and secondly, a classification of water demand of trees. The term ‘water demand’ is not defined by the NHBC; however, a definition given by Biddle [2] is “the ability of vegetation to cause drying of a clay soil”. Tree species have been ranked by NHBC as having low, moderate or high water demand, taking into account the radial extent and depth of tree roots. However, published scientific data on the water demand of trees of various species in urban environments to support the classification are very rare, and some criticism has been levelled at the categorization of species for this reason [25]. Criticism has also been levelled at the application of the guidelines to all of the country, despite research findings emanating from just a “60 km radius of central London” [25].

The Australian Standard—Residential slabs and footings (AS2870)—was first published in 1986 to regulate different practices across the States and cut the incidence and costs of damage to light-weight buildings [16]. Until the 2011 edition, the standard did not provide any guidance for designing footings in the vicinity of a tree or group of trees. Instead, the emphasis was placed on the importance of good site maintenance and general guidance was provided for property owners to avoid abnormal/extreme soil moisture changes around their dwelling within the 50 year design life of the dwelling. In particular, it was stated that trees should be kept sufficiently far away relative to their heights and grouping (i.e. proximity rules), so that the vegetation was unlikely to have any influence on footing movement [15]. For example, a footing was assumed to avoid tree root drying effects if constructed from a distance equal to the mature height of the tree in the case of a single tree. The distance was increased to 1.5 times the tree height ( $H$ ) for tree groups and  $2H$  for a row of trees (3 or more) [27].

A majority of Australian homes are single or double-storey houses, which are comprised of traditional timber framing internally with a single layer of masonry on the

outside (brick veneer construction). This type of structure is reasonably intolerant of ground movements in an area covered with expansive clays [22, 29], although it is common practice to provide regularly spaced vertical joints in the masonry to improve flexibility. According to the current edition of the standard [27], the design site can be categorized into one of five classes (Table 1) where ground movement is primarily arising from soil expansivity. The characteristic ground surface movement ( $y_s$ ) based on the design life of the house is employed to conduct site classification and is determined using Eq. 1.

$$y_s = \frac{1}{100} \sum_{n=1}^N (I_{pt} \overline{\Delta u} h)_n \quad (1)$$

where  $N$  is the number of layers within the depth of design suction change  $H_s$ ;  $I_{pt}$  is the instability index, representing the degree of soil reactivity at the site, which can be determined from the shrink-swell index,  $I_{ss}$ , moderated by consideration of the depth of potential shrinkage cracking and therefore potential lateral restraint;  $h$  is the thickness of the soil layer, and  $\overline{\Delta u}$  is the mean soil suction change for the soil layer considered.

Domestic dwellings constructed in the early 1990s are subjected to greater risks of damage than recently built houses because those structures were not designed to cater for tree root drying effects. AS2870 [27] embellished the ‘tree proximity rule’ by providing extra design suction changes and a deeper change ( $H_t \geq H_s$ ) usually to help to account for the influence of trees. The maximum design suction change occurs in close proximity to a tree (half the height), but then may decrease progressively as proximity is relaxed. Additional ground movement due to trees may be estimated based on the design suction changes. These guidelines are based on simplistic empiricism and very limited field data and measurement. Water uptake of different tree species in an urban environment was not included in the formulation of the guidelines. In the absence of such information, inappropriate sizes of footings can be designed, leading to either excessive construction cost or potential footing failure.

**Table 1** Site classification by  $y_s$  [27]

Ground surface movement ( $y_s$ ) mm	Site class	Site reactivity
0–20	S	Slightly reactive
20–40	M	Moderately reactive
40–60	H1	Highly reactive
60–75	H2	Very Highly reactive
> 75	E	Extremely reactive

Therefore, local knowledge of specific tree species in an urban environment is required, and case studies are particularly needed to promote the understanding of tree water use and possible damage caused by tree drying settlement. In this study, the water demand of a large spotted gum tree, an Australian native species, was closely monitored using Sap Flow Meters (SFM1). Preliminary results obtained from the well-established field site were used to assess the influence of tree root drying on ground movements and soil moisture/suction variation.

## 2 Description of tree site

A reserve in the suburb of Bayswater, located approximately 29 km east of Melbourne's CBD (Victoria, Australia), was selected for field site instrumentation and tree monitoring. The site is 80 m above sea level and is relatively flat, grassed and contains no apparent geological anomalies. The study area is composed of quaternary alluvium (Qra) and generally contains grey or yellow-brown mottled duplex soils. A large spotted gum (species: *Corymbia Maculata*) is located in clay soil in the vicinity of the asphalt footpath as shown in Fig. 1. The tree height of 14.5 m was measured using a clinometer. The diameter



Fig. 1 A large 14.5 m high spotted gum

at breast height (DBH) was 0.42 m, as calculated from the circumference of the main tree trunk measured using a fibreglass tape measure. This species was chosen for the study because it is the most common planting on nature strips alongside the street as well as in reserves and parks. Six fabricated galvanized steel panels (1.0 × 2.0 m) were installed to secure the tree monitoring device and external power supply system.

Melbourne, the state capital of Victoria and second largest city in Australia, is classified as being in climate Zone 3 [20, 30], having a temperate climate with balmy and mild spring and autumn, warm-hot summers and cool winters. The selected site has experienced significant seasonal variations with average temperature ranges from 18.0 to 20.3 °C during summer periods (December to February) and 9.4 to 10.3 °C for winter months (June–August). The mean annual rainfall and solar exposure are, respectively, 858.5 mm and 14.6 MJ m<sup>-2</sup> [5]. The mean weather data are based on historical long-term observations from 1948 to 2018.

## 3 Site instrumentation

The layout of site instrumentation is depicted in Fig. 2. The monitoring instruments and aids were installed during September 2017 and included: (a) ground surface and sub-surface movement concrete pads; (b) ground surface movement pins embedded in the footpath; (c) neutron soil moisture meter gauge access tubes; (d) in situ psychrometers; (e) sap flow meter.

### 3.1 Laboratory soil testing

To assess soil profile and the degree of expansivity for different soil types, two 40 mm diameter boreholes (BH) were drilled to a depth of 4 m, at a radial distance of 6.0 m (tree's drip line) and 14.6 m from the trunk of the tree. Borehole locations coincided with neutron moisture meter gauge access tube locations. The soil profile of BH 1 is described in Table 2. Generally, the soil consisted of one metre of fill, which included top soil (or clayey silt) in a layer of 0.1 m thick, underlain by low-plasticity silty clay, becoming high plasticity to the full depth of exploration of 4 m. The presence of tree roots of various diameter (0.1–1.5 mm) was observed infrequently between 0.75 m and 1.75 m. A similar soil profile was found for BH 2, with deep fill up to approximately 1.75 m; however, there were no tree roots observed throughout the soil profile.

Atterberg limits tests (plastic limits, PL and liquid limits, LL) were conducted, and the results are presented in Fig. 3a–b. Plastic limits varied from 13 to 20%, while liquid limits ranged between 37 and 53% within the top

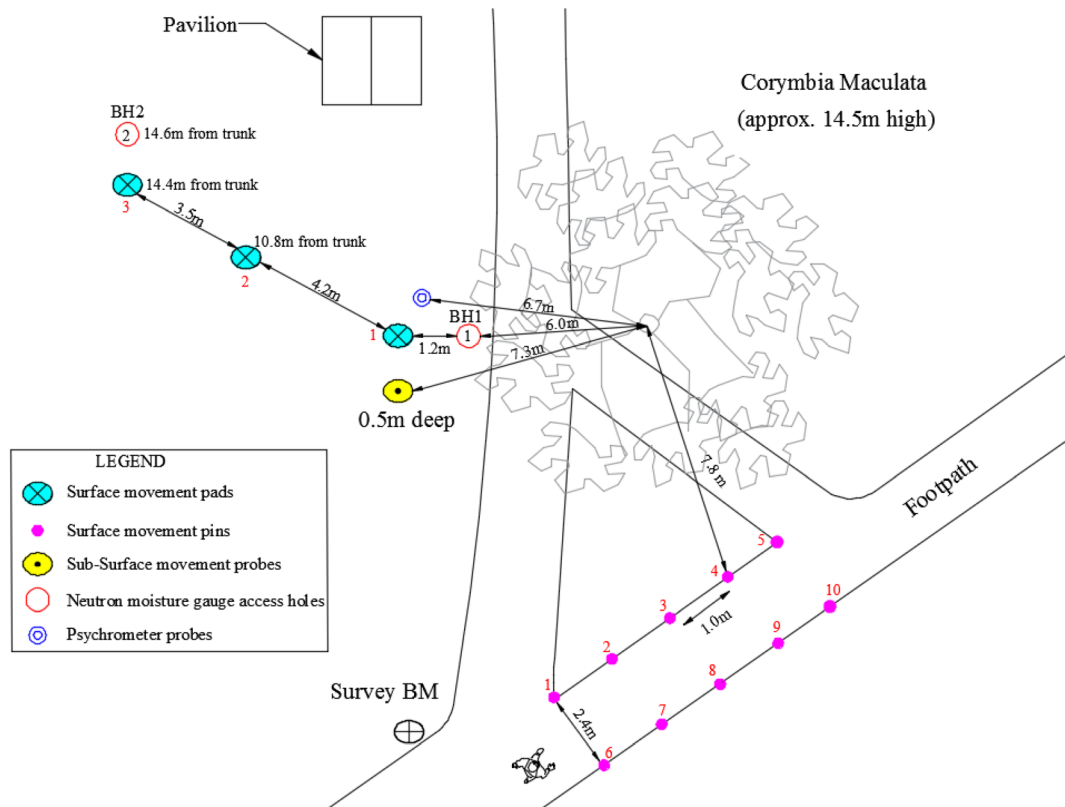


Fig. 2 Location of site instrumentation (not to scale)

Table 2 Description of soil profile of BH 1

Depth (m)	Soil description
0.00–0.10	Fill—Silty loam (ML), dark brown, moist
0.10–1.00	Fill—Silty clay (CL), dark yellowish brown, becoming very dark grey below 0.6 m, moist, stiff, with sub-rounded to angular gravels, tree rootlets presented
1.00–1.75	Silty clay (CL), light brownish grey, mottled pale yellow, moist, soft to firm, very fine tree rootlets presented
1.75–2.00	Silty clay (CL), dark to very dark yellowish brown, moist, stiff
2.00–2.60	Silty clay (CH), very dark greyish brown mottled dark yellowish brown, wet, stiff
2.60–4.00	Silty clay (CH), yellowish brown mottled grey, wet, very stiff, borehole terminated at 4 m depth

2 m, followed by a marked increase up to 82% at 3 m with little change at a depth of 4 m.

Soil from the borehole which was employed to install in situ psychrometers was used to perform the shrink-swell test at different depths. Shrink-swell test includes a swelling test and a simplified core shrinkage test. Two “companion” soil samples containing the same initial moisture content are required. For the simplified core shrinkage test,

the cylindrical soil specimen is cut and trimmed to a length of 1.5–2 diameters. A steel pin was inserted in the centre of both the top and bottom end of the core sample, providing a reference mark for measurements of length changes to be performed. The core samples were allowed to air dry on a smooth surface for about two weeks and then oven-dried to a constant mass. The changes in sample diameter, mass and length were closely monitored with time. The swell test requires a soil sample to be cut to a diameter of 45 mm and a height of 20 mm using a rigid steel ring and then trimmed carefully to ensure flat ends on both sides. Two porous stone plates were mounted at the top and bottom of the sample before being placed in a consolidation cell. An initial seating pressure of 5 kPa was applied for about 10 min before increasing the vertical pressure to 25 kPa for no more than 30 min to allow for any initial soil settlement. Swelling strains were calculated taking any initial dry settlement into account. Thereafter, distilled water was added to the cell to observe any swell. A detailed description of conducting the shrink-swell test is given by Li et al. [21].

The shrink-swell index,  $I_{ss}$ , represents the rate of change of vertical strain with a unit change of the logarithm of suction in kPa, or a unit change of the logarithmic pF measure. Values of 1.7 and 0.5%/pF were obtained for samples from 0.8 m and 1.7 m deep, respectively. The



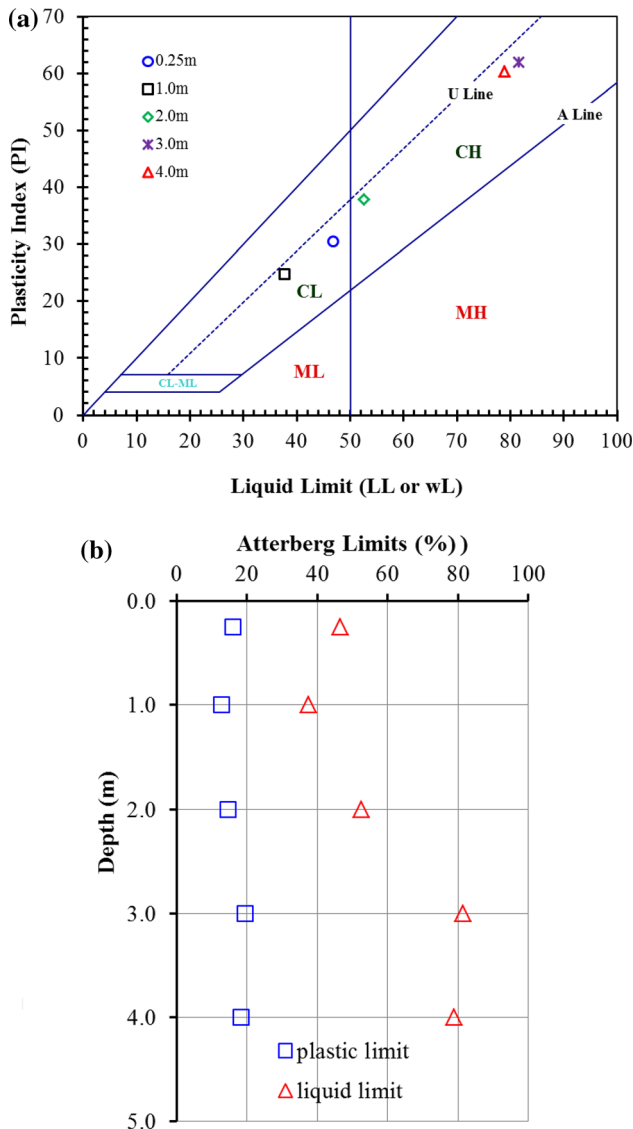


Fig. 3 Soil properties of samples from BH 1 a plasticity chart; b test results of PL and LL

design total suction change profile for the site from AS2870 [27] is presented in Fig. 4.  $\Delta u_s$  is the maximum design suction change which occurs at the ground surface; 1.2 pF may represent a change in total suction from 195 kPa to 3.09 MPa (3.3–4.5 pF), or something similar. For simplicity, the design suction change is assumed in AS2870 to vary linearly with depth to 0 pF (0 kPa) at the depth of design soil suction change ( $H_s$ ). At this depth, no marked variations in soil suction are expected to occur as a consequence of weather changes. For eastern Melbourne, a  $H_s$  of 1.8–2.3 m and cracking depth of 0.75  $H_s$  (i.e. 1.73 m) are recommended by AS2870 [27]. The characteristic ground movements  $y_s$  of 18 mm can then be calculated using Eq. 1, and the site is classified subsequently as Class S (slightly reactive, refer to Table 1).

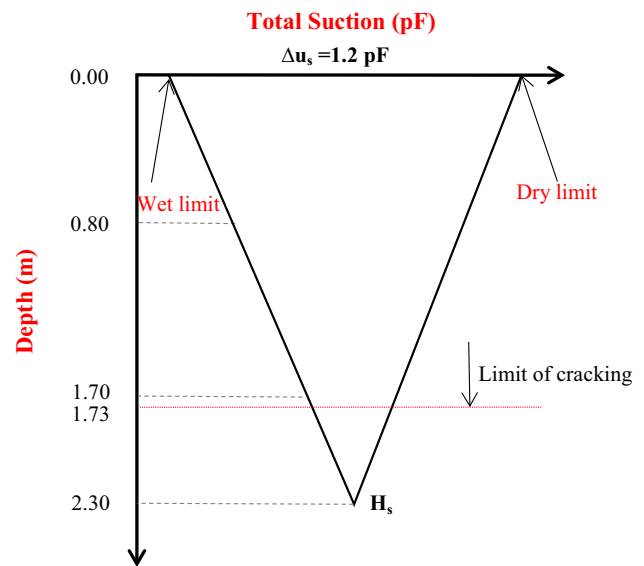


Fig. 4 Typical design suction change profile

The soil water characteristic curve (SWCC) indicates the capacity of soil to store or release water when subjected to matric suction control. SWCC is defined as the relationship for unsaturated soils between matric suction and the degree of saturation or volumetric water content, or gravimetric water content [28]. The SWCC was determined in the Laboratory of RMIT University primarily using the Fredlund SWCC device (SWC-150) for suctions from 0 to 1500 kPa, and a Decagon dewpoint potentiometer (WP4) for suction above 1500 kPa. The Fredlund SWCC device uses the axis translation technique, allowing the control of matric suctions from near zero values up to 1500 kPa by the use of dual pressure regulators and precise gauges, while holding sample pore-water pressure equal to atmospheric pressure. The soil sample from a depth of 0.7 m was carefully trimmed to size (450 mm in length and 50 mm in diameter) and immersed in distilled water for two weeks to achieve full saturation before being placed into the stainless steel SWCC cell. The test was conducted by increasing matric suction from 20 to 1100 kPa progressively in 7 steps, at a token vertical pressure of 10 kPa, which provided a positive contact between the soil specimen and the ceramic disc. The contact between the soil and the ceramic disc is essential for efficient water flow to and from the soil specimen. The specimen was removed from the Fredlund SWCC device once the matric suction reached 1100 kPa. It was then stored in a vacuum desiccator apparatus over a sodium chloride (NaCl) solution for about 4 weeks to enable a further suction-moisture content point for the SWCC using the WP4 dewpoint potentiometer. The WP4 was calibrated using a 0.5 Molal/kg solution of potassium chloride in accordance with the manufacturer’s manual. The SWCC data obtained from

measurement were fitted with the equation provided by Fredlund and Xing [14], as shown in Fig. 5. The starting and end points to the curve were assumed constraints.

### 3.2 Ground surface and sub-surface movement probes

Level surveys were carried out on a regular basis (i.e. every 3 weeks) to monitor the impact of tree root drying effects on the ground surface and sub-surface movement. Three surface movement pads were installed at various distances from the tree trunk (Fig. 2). These were 100 mm high pads cast in a 100 mm diameter concrete mould, with a flanged hex nut installed at the centre of the pad, so that the measuring staff can be seated on top of the nut when taking a reading during a level survey. Ten galvanized steel pins were also installed along the edge of the 2.4 m width footpath, approximately 7.8 m away from the tree, to assess tree root desiccation induced movement of the asphalt pavement.

Sub-surface movement probes consisted of a 75 mm diameter, 50 mm high cylindrical shaped concrete base, which was cast in a concrete mould, with a 0.5 m length of galvanized steel bar embedded in the centre of the base. PVC pipes of 90 mm diameter were pushed into two pre-drilled holes to depths of 0.5 m; movement probes were then placed at the bottom of the hole in contact with soil and secured using a cap at the top end of the PVC pipe. The gap between the borehole wall and the PVC sleeve was backfilled with soils from the same borehole and a mixture of bentonite pellets and concrete.

### 3.3 Neutron moisture meter (NMM)

The Campbell Pacific Nuclear Model 503DR neutron moisture meter (NMM) was employed to provide an estimation of long-term in situ soil moisture changes with depth, with measurements taken at selected depth intervals

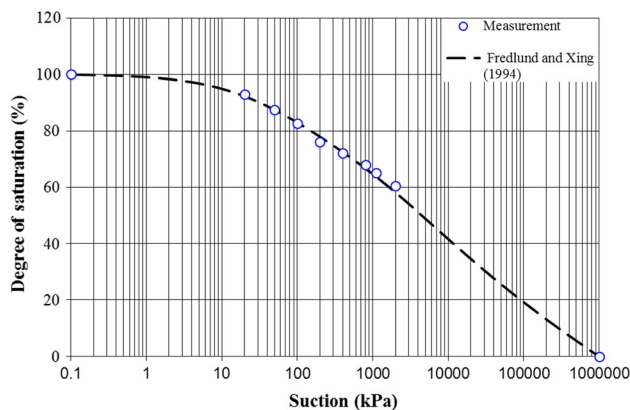


Fig. 5 Degree of saturation versus soil suction

within the access tube on a regular basis (i.e. every 3 weeks). As shown in Fig. 2, two neutron probe access holes were drilled to a depth of four metres at two different distances from the tree trunk. Then, a thin-walled (i.e., 2 mm) aluminium tube of 50 mm diameter was inserted into each borehole. The bottom end of the access tubes was sealed, while the top end was protected with a GATIC® access cover to prevent rainwater entering.

The neutron moisture meter (NMM) consists of a probe connected by cabling to a logger. The probe is lowered down the aluminium access tube in contact. Cable ties used as stops were attached to the cable at every 0.25 m up to 1 m and at every 0.5 m from 1 to 4 m (e.g. length of the access tube), allowing the probe to be positioned at the designated depth in the access tube. The NMM probe includes a radioactive source (Americium Beryllium  $^{241}\text{AmBe}$ ), which emits fast neutrons and a Helium-3 detector (13.2 cm in length, 2.54 cm in diameter) that measures the amount of thermalized neutrons. When the NMM probe is held in position at a depth, the fast neutrons emitted by the source collide mainly with hydrogen atoms (e.g. water) in the soil. Hydrogen thermalizes (slow) neutrons most effectively as the atoms' similar size results in an energy losing elastic collision. The number of thermalized neutrons returning back to the detector within the selected count time is directly proportional to the amount of water present in the surrounding soil, i.e., the higher the count, the greater the volume of moisture in the soil [18].

The neutron count is commonly normalized by the background count taken, while the NMM sits in its protective housing (or other chosen standard medium) on the day of monitoring, resulting in a neutron count ratio (NCR). Reactive soils in the field can shrink on hot and dry days, resulting in a gap between the borehole wall and the



Fig. 6 In situ soil suction measurement



**Fig. 7** SFM1 for sap flow rate monitoring

access tube which allows ingress of rainwater and thus makes the calibration more complicated [18, 19].

### 3.4 In situ psychrometer

To obtain long-term soil suction (water potential) data at the field site, three Wescor PST-55 in situ soil psychrometers were buried at various depths (i.e. 0.4 m, 1.4 m and 2.3 m) at a distance of 6.7 m from the trunk of the tree. A GATIC access cover was installed to prevent rainwater entering and vandalism (Fig. 6). The PST-55 has an ultrafine Dutch weave stainless steel screen to allow water vapour equilibrium with the surrounding bulk soil, and the gold plated internal connections protect the psychrometric

thermocouple from corrosion, even in hostile soil environments. Discrepancies in the thermocouple junction geometry lead to variation in the soil water potential measurement. Therefore, each thermocouple has unique electrical output characteristics. Each psychrometer was calibrated with sodium chloride (NaCl) solution at various concentrations in a customized temperature-controlled chamber before deployment. The suction measure is dependent on the establishment of water vapour pressure equilibrium between the soil moisture and the air above the soil under isothermal conditions. Soil suction reading was performed regularly by using Wescor PSYPRO Water Potential System, with a measurable range of  $-0.05$  MPa and  $-8$  MPa and accuracy ranging from  $\pm 0.1$  MPa to  $\pm 0.01$  MPa, depending on thermal stability and other factors.

### 3.5 Sap flow meter SFM1

The Sap Flow Meter SFM1 (Fig. 7) has been used for the scientific study of sap flow since 1996, and the accuracy and reliability have been assessed against an independent measure of transpiration (i.e. gravimetric measurements) by Burgess [6]. It is capable of accurately measuring a wide variety of tree species in different environmental conditions that generate zero, low, high and reverse sap flow rates. In this study, SFM1 has been employed to measure sap velocity and sap flow volume (transpiration) of the large spotted gum tree. Sap velocity and flow volume are based on the heat ratio method (HRM), which measures the ratio of the increase in temperature, following the release of a heat pulse, at points equidistant downstream and upstream from a line heater. The SFM1 is comprised of three measurement needles (two temperature needles and one heater needle) and a data logger with integrated software for data downloading. Each needle is attached to the SFM1 independently through a cable and is colour-coded and labelled to differentiate its function and signify the installation position. The needles are made of a 35 mm



**Fig. 8** Sapwood estimate by applying an indicator dye



**Table 3** Basic wood properties of the spotted gum tree

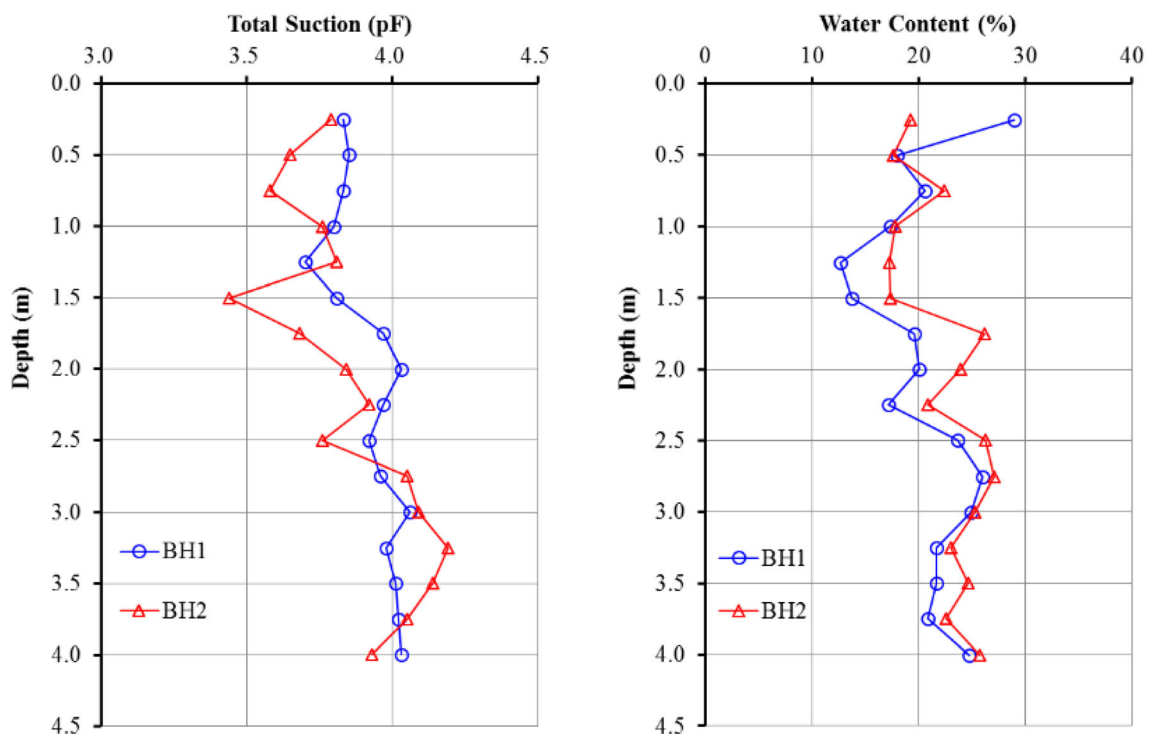
Trunk circumference (m)	Bark depth (mm)	Sapwood depth (mm)	Heartwood depth (mm)	Xylem radius (mm)	Sapwood area (cm <sup>2</sup> )	Basal area (cm <sup>2</sup> )
1.3	2.2	66.8	139.4	206.3	725.8	1,365.6

long, 1.3 mm diameter hollow stainless steel tubing. Temperature needles contain two thermistors located 12.5 mm and 27.5 mm from the base of the measurement needle. The heater needle consists of high resistance wires that dissipate power and produce a high amount of heat efficiently in a short pulse.

Tree bark was removed locally, and the drill guide for accurate positioning of the needles was attached to the tree trunk before installation of the SFM1 at breast height. A small amount of silicon grease was smeared onto each needle before insertion into the pre-drilled holes. Plastic cable ties were used to secure the SFM1 device to the tree trunk. Two 12 V external batteries in series are directly connected to the non-polarized charging ports to charge the 4.2 V (1000 mA) lithium-polymer internal battery for continuous field monitoring. Batteries were secured in a stainless steel box (40 × 21 × 40 cm), which was placed on a concrete block to prevent the ingress of rainwater or from water ponding during a prolonged rainfall event.

Small cores were taken from the tree to determine sapwood depth, which was needed for the determination of the conductive sapwood volume. A 400-mm-long incremental borer with a diameter of 5.15 mm was used to extract cores. The borer was taken halfway into the tree trunk to ensure that the core passed through the sapwood into the heartwood. Sapwood depth was estimated by applying an indicator dye (methyl orange) after the core was removed from the borer. The sapwood turned yellow and the heartwood a deep red colour (Fig. 8). A digital vernier calliper was used to measure the sapwood depth.

Table 3 presents the basic wood properties of the spotted gum. Bark thickness was determined at DBH by averaging four sets of measurement at several locations using a bark depth gauge, while the trunk circumference was measured by employing a fibreglass tape measure. Tree xylem radius is the sum of sapwood depth and heartwood depth. Tree basal area (TBA) is the cross-sectional area (over the bark) at breast height. It is interesting to note that 53 percent of

**Fig. 9** Soil suction and moisture content profiles for BH 1 and BH 2 in early spring



the TBA is sapwood, assuming cross section of the tree is symmetrical.

## 4 Preliminary results

All on-site monitoring instruments and accessories had been installed by September 2017. The preliminary results over a 6-month period for soil suction change, soil moisture variation, ground surface and sub-surface movement and transpiration of the spotted gum are presented in the following sections, beginning with soil moisture and suction data.

### 4.1 Soil suction change and moisture variation

Two boreholes were drilled at different distances from the main trunk of the tree in September using a hydraulic drilling rig. The soil samples taken from the borehole core were wrapped every 250 mm using cling film and sealed immediately with zip-lock bags upon sample extraction from thin-walled stainless steel tubes and subsequently were tested for total suction using the WP4 in the Laboratory of RMIT University. Reported suction was based on an average of three subsamples. Gravimetric soil water content was determined using the oven drying method in accordance with Australian Standard AS1289.2.1.1 [26].

The total soil suction profiles for each of the two boreholes near the spotted gum tree in early spring are presented in Fig. 9. It may be observed that soil desiccation arising from tree drying effects was evident at 1.5 m below ground surface for BH 1 (i.e. dip line), and then, soil suction remained constant at approximately 4 pF (980 kPa) below 3 m, which could be considered as the equilibrium suction for the site. This value is higher than the equilibrium suction of 3.63 pF (420 kPa) estimated by Cameron [7] for a site near the bay in Melbourne in the western suburb of Williamstown. Soil suction profile of BH 2

reveals that the soil further away from the tree is wetter than the soil from BH 1 between depths of 0.5 m and 2.5 m which is confirmed by measured moisture contents as shown in Fig. 9. Such suction is considered as the usual for a soil profile unaffected by the tree. It is worth noting that unusually higher suction was observed between 3 and 3.75 m for BH 2, although the corresponding water content profiles over these depths contradicted this observation as the moisture contents were slightly higher compared to those in BH 1.

### 4.2 Soil movement

Measurement of ground surface and sub-surface movements was conducted using the Trimble Spectra Precision laser level (with a resolution of 0.01 mm) on a monthly basis, and the initial readings were taken during the tree growing season in October. Location of surface pads, surface pins and sub-surface probes in relation to the tree is depicted in Fig. 2. Surface and sub-surface levels were measured relative to the arbitrary reduced level of the “benchmark”. Level survey data for the initial observations are presented in Figs. 10, 11. Ground movement is determined against the original level, just after installation in October 2017. Positive movement is an indicator of heave, while soil settlement is expressed by negative movement. It can be seen from Fig. 10 that soil closer to the tree’s drip line (i.e. surface pad 1) experienced the greatest, although minor, shrinkage settlement compared to soil most distant from the tree. A relatively small soil settlement has occurred at 0.5 m depth at a distance of 7.3 m from the tree trunk.

Apparent movements of ten ground surface steel pins installed alongside the asphalt footpath are shown in Fig. 11. It can be seen that soil movements under the pavement exhibited similar variation trends except for Pin (8), which moved down prior to January 2018 and then went up before February 2018 when the rest of the pins

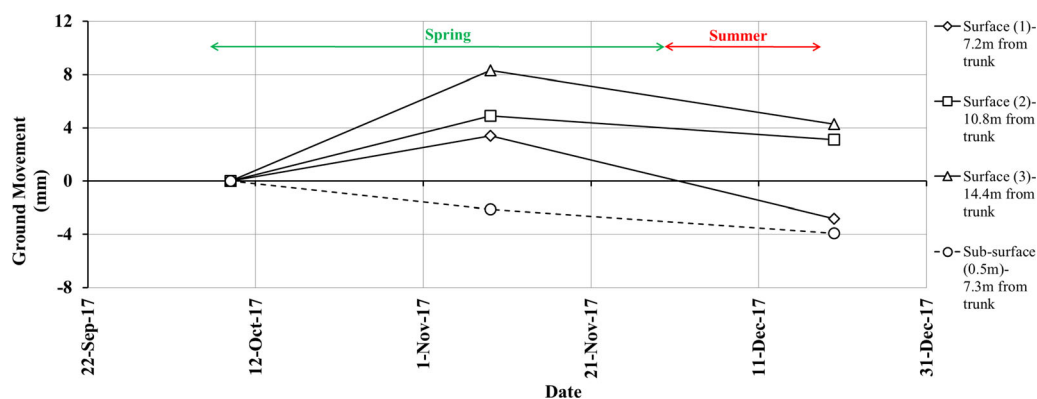


Fig. 10 Ground surface and sub-surface movement

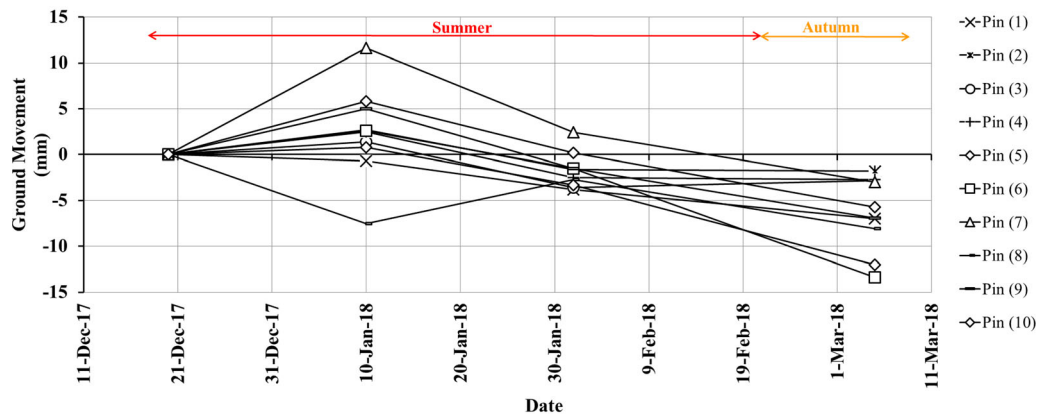


Fig. 11 Movement of ground surface pins

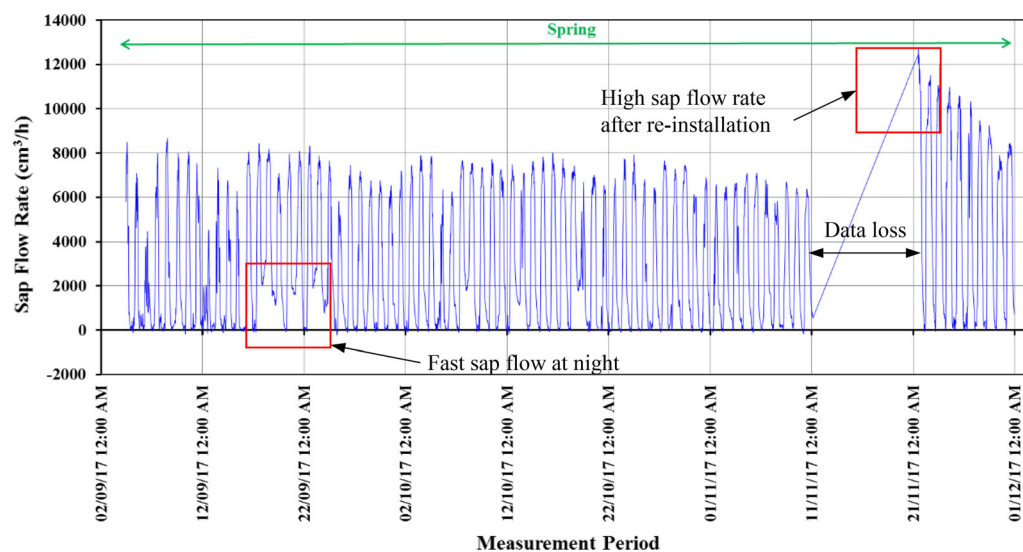


Fig. 12 Sap flow rate against time

went in the opposite direction. It is also notable that Pin No. 7 suffered a greater heave, whereas No. 8, which is 1 m away, experienced the largest settlement when the level survey was conducted during January 2018. Overall, the continuous shrinkage settlement for almost all survey pins since January 2018 may be explained by the higher water demand of tree roots during summer periods.

### 4.3 Water demand of a large spotted gum tree

An SFM1 was installed on the north side of the main trunk of the tree at breast height to monitor sap velocity and transpiration rate of the large spotted gum. The heat pulse released by the heater (i.e., red needle) and the logging frequency was set to be 15 Joule and 30 min, respectively. Sap flow mode was chosen as the reporting option since

prior knowledge about the tree (e.g., tree species, bark thickness and depth of sapwood) had been obtained and recorded on each sap flow meter.

The pattern of measured sap flow rate during spring periods (September to November) is depicted in Fig. 12. It is evident that diurnal courses of sap flow present a bell-shaped curve, with the maximum flow rate occurring in the early afternoon and thereafter decreasing gradually until approaching zero at midnight. During monitoring on clear days, a significant amount of water flowed through the trunk at night, as shown at the bottom left (red mark) of Fig. 12. This is probably because water extracted during the day did not meet the water demand of the tree. As shown in Fig. 12, 10 days of monitoring were lost in November due to SFM malfunction. High sap flow rate presented at the top right (red mark) was the consequence

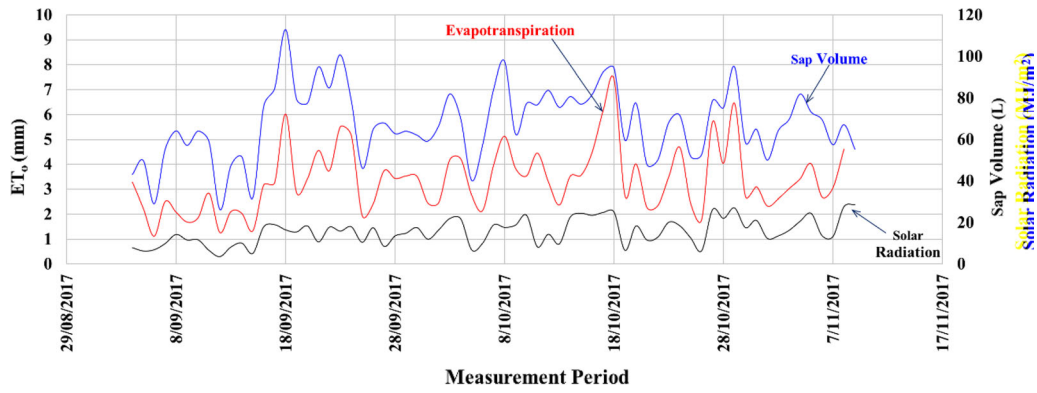


Fig. 13 Variation trend of tree transpiration, evapotranspiration and solar radiation

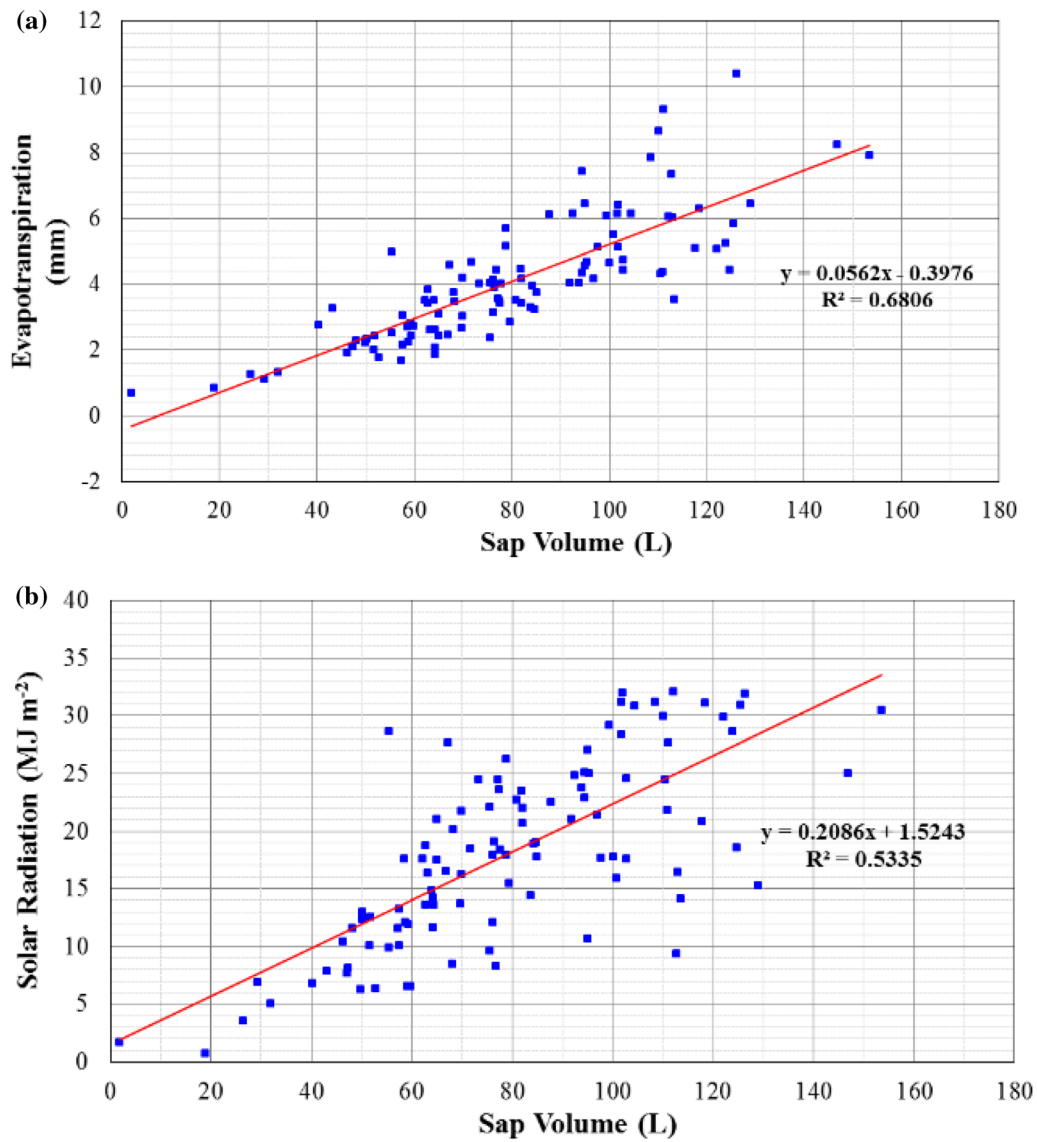


Fig. 14 Correlation of weather parameters a correlation between sap volume and  $ET_0$ ; b correlation between sap volume and solar radiation



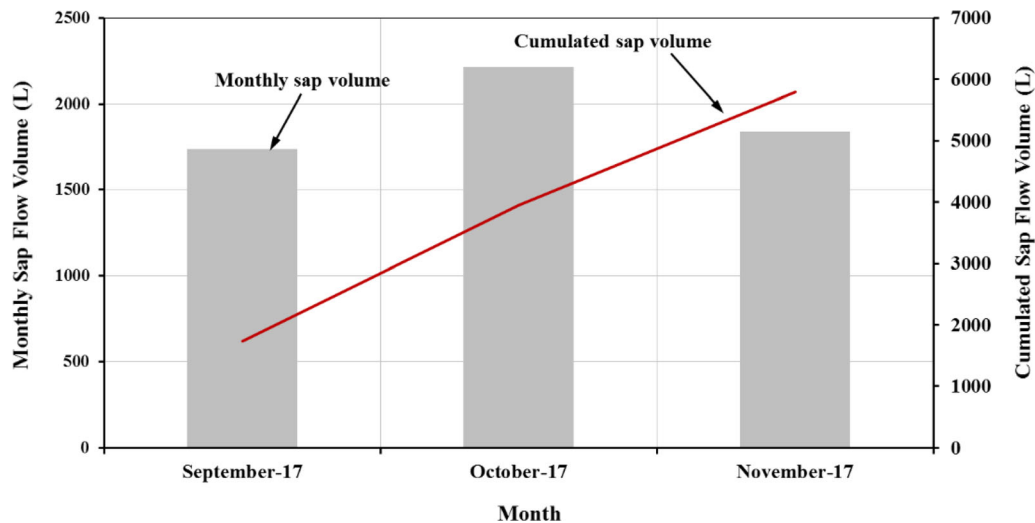


Fig. 15 Sap flow volume for spring months

of SFM1 re-installation (installed in exactly the same position as before) as the tree would need a few days to recover the wound which allowed the accurate (normal) measure to be made.

Daily variation of transpiration of the spotted gum was compared with solar radiation and daily reference evapotranspiration ( $ET_o$ ), as depicted in Fig. 13.  $ET_o$  was estimated using ASCE Standardized Penman–Monteith equation based on the short reference vegetative cover of 0.12 m (e.g. grass). Latent heat of vaporization of 2.45 MJ/kg was adopted, and a value of 0.23 is assumed for albedo of reference surfaces. Meteorological parameters (e.g. air temperature, solar radiation and humidity, etc.) required in calculating  $ET_o$  were obtained from weather station (Scoresby Research Institute, No: 086104) located approximately 3.5 km from the study site. Description of all the parameters in the equation and the methods in calculating  $ET_o$  is beyond the scope of this paper and can be found in Allen et al. [1]. Figure 13 reveals that tree water use is highly variable from day to day. As well, daily transpiration of the tree had a similar trend of variation with both solar radiation and  $ET_o$ .

Potential correlations of daily transpiration with these two weather parameters were appraised using the coefficient of determination ( $R^2$ ), which is a statistical measure of how close the data are to the fitted regression line. Correlations were classified into one of five categories from 0, indicating no correlation to 1 representing very strong correlation [12]. Figure 14a shows a moderate, positive, linear relationship between sap volume and  $ET_o$  with  $R^2$  of 0.68. A smaller  $R^2$  of 0.53 was calculated for the linear correlation between sap volume and solar radiation

(Fig. 14b), indicating a reasonable agreement between the two parameters.

Figure 15 presents the monthly sap flow volume (transpiration) and the cumulated sap volume in litres for the three months of monitoring. It should be noted that the total sap volume presented in November is for just for 20 days because of data loss as a consequence of equipment malfunction. The actual total sap volume in November was expected to be the highest during spring periods; the daily transpiration varied from 29 L at the start of September to 153 L at the end of the spring period.

Mean daily transpiration volumes of 64, 71 and 92 L were calculated for September, October and November, respectively, which showed that the tree water demand started to increase since September and the largest mean daily transpiration occurred in November.

## 5 Conclusions

In Melbourne, the capital city of the State of Victoria, many light-weight residential dwellings constructed on reactive clay soils are vulnerable to ground movements due to its prevailing temperate climate which can result in shrinkage and swelling of soils. The presence of trees is likely to exacerbate such movements as a result of tree root-drying effect. In this study, a field site was established and fully instrumented to assess the influences of a large spotted gum tree on soil desiccation and soil movements. Soil moisture variation, soil suction change, ground surface and sub-surface movements were closely monitored using, respectively, neutron moisture meter (NMM), in situ soil psychrometer and laser level on a regular basis. To

measure sap velocity and transpiration rate of the large spotted gum tree, a SFM1 was installed on the north side of the main trunk of the tree at breast height.

The preliminary monitoring results have been presented in this study and are summarized as follows:

The sapwood area occupied as much as 53 percent area of the main trunk of the tree at the level of coring (e.g. DBH), assuming cross section of the tree is symmetrical. The initial suction profile for BH 1 at the drip line of the tree suggests soil desiccation has occurred at 1.5 m depth, which is most likely due to the higher density of tree roots, while suction and water content measured on samples further away (BH 2) indicated largely that soil distant from the tree was relatively wet.

Level survey results reveal that surface and sub-surface (0.5 m) soil near the drip line had suffered different extents of shrinkage settlement compared to soil way from the tree.

Sap flow rate pattern exhibited a bell-shaped curve, with the maximum flow rate occurring in the early afternoon and then a gradual decrease to usually near-zero at midnight.

Some sap flow occasionally occurred at night, presumably because water extraction in the daytime could not meet the demand of the tree.

Tree water use was highly variable from day to day, depending on weather patterns. Daily transpiration of the tree as measured by the sap flow meter followed reference evapotranspiration  $ET_0$ , quite closely and displayed a moderate linear correlation.

Daily water demand of the large spotted gum tree ranged between 29 and 153 L during the spring months.

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