Transpiration and the water balance of tree-based stormwater control measures

Transpiration et bilan hydrique de techniques alternatives intégrant des arbres

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RÉSUMÉ

Les techniques alternatives sont utilisées de plus en plus afin de capturer, retenir et utiliser les eaux pluviales provenant des surfaces imperméables. Les surfaces imperméabilisées empêchent l'infiltration et elles augmentent également le ruissellement. L'intégration d'arbres dans les techniques alternatives offre plusieurs services écosystémiques, y compris la rétention d'eau pluviale. Cette étude quantifie la transpiration des arbres d'alignement, à proximité d'une tranchée d'infiltration, et compare les performances (i) des petits (jeunes) arbres et (ii) des grands (matures) arbres. L'étude montre que la taille de l'arbre a un effet significatif sur la transpiration ; les grands arbres ont transpiré 30% du ruissellement généré par le bassin versant, alors que les petits arbres ne transpirent que 6% du ruissellement. L'intégration d'arbres dans les ouvrages de gestion des eaux pluviales contribue à un bilan hydrique plus naturel, et leur performance augmente au cours de temps, en fonction de la croissance d'arbres.

ABSTRACT

Stormwater control measures are increasingly used to capture, detain and use stormwater runoff created by impervious surfaces. In addition to increasing runoff, impervious surfaces restrict the water available to trees in cities due to reduced infiltration into urban soils. Integrating trees into stormwater control measures may be able to reduce runoff while also providing additional benefits. We installed infiltration trenches at two sites adjacent to i) small establishing street trees, and ii) more established street trees. We compared transpiration of these trees with stormwater runoff and retention of the infiltration trenches, to assess the potential benefits of integrating trees with stormwater management. Tree size had a large impact on transpiration relative to stormwater runoff. Large trees transpired up to 30% of runoff generated by the catchment, which exceeded the volume of stormwater intercepted by infiltration trenches in some months. Small trees transpired up to 6% of runoff, such that the volume of transpiration was always less than the volume of stormwater intercepted. Integrating trees with stormwater management clearly provides multiple benefits and may increase the proportion of stormwater runoff that can be retained, especially as trees establish.

KEYWORDS

SCMs, Transpiration, Trees, Water Balance

1 INTRODUCTION

1.1 Background

Stormwater control measures (SCMs) are increasingly being installed in cities to harvest, detain, and use stormwater runoff created by extensive impervious surfaces (Grey et al., 2018b). Infiltration-based measures such as trenches, swales or pervious pavements reduce the volume of stormwater through retention, infiltration and evapotranspiration (Fletcher et al. 2013). Evapotranspiration is often considered a small component of the water balance of SCMs relative to large volumes of runoff generated by rainfall, especially for systems planted with sedges and rushes (Daly et al. 2012). Trees provide many benefits in cities and can transpire large volumes of water daily, depending on their size and wood characteristics (Litvak et al. 2017), Yet, they often experience low water availability due to reduced rainfall infiltration through impervious surfaces. Integrating trees into SCMs may provide multiple benefits by simultaneously increasing the evapotranspirative proportion of the water balance of stormwater control measures, as well as reducing urban heat. This study aims to assess the potential benefits of integrating trees with stormwater management and how the contribution of tree transpiration to the water balance of SCMs varies with system design and tree size.

2 METHODS

2.1 Study site and experimental setup

Two experimental study sites with infiltration trenches installed adjacent to street trees were compared, to assess the potential differences in the contribution of transpiration to the water balance of stormwater control measures (SCMs). The first site (MONASH) was located in a medium-density residential street and included large, established trees and the second site (MORELAND) was located in a high-density residential street, planted with small establishing trees (site comparison in Table 1 and Fig. 1).

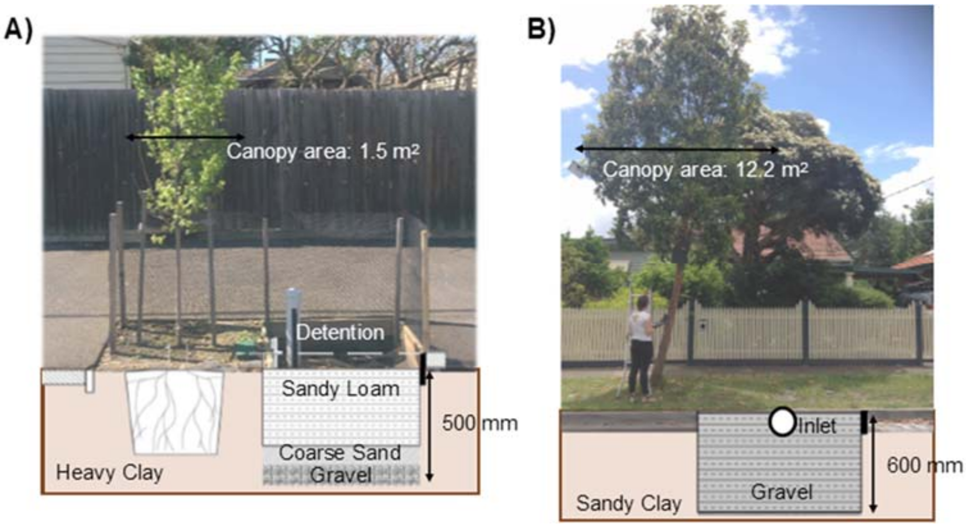

Figure 1: Schematic illustration of differences between the A) MORELAND and B) MONASH sites.

Table 1: Between-site comparison of environmental, design, and tree characteristics

Characteristics	Description	MORELAND	MONASH
Environment	Rainfall at the site	281.8 mm (276.3)	228.6 mm (144.1) – 2015/16
	Initial loss	0.1 mm	0.5 mm
	Number of events	55	53
Design	Surface area	0.72 m^2	6 m^2
	Catchment size	153 m^2 (100 to 160 m^2)	203 m^2 (154 to 254 m^2)
	System size: catchment area	0.5% (0.4 – 0.7%)	3.1% (2.4 to 3.9%)
Tree	Species	*Acer campestre*	*Lophostemon confertus*
	Phenology	Deciduous	Evergreen

2.2 Transpiration

2.2.1 Sap velocity

Sap flux was measured with SFM1 sap flow sensors (ICT International, Armidale, Australia) that utilise the heat ratio method (Burgess et al. 2001). Briefly, three needles are inserted equidistantly into the tree xylem, with two temperature sensors inserted above and below the central heat-emitting needle. Sap velocity is determined by the difference in temperature between the two sensors following a heat pulse from the central needle. Data were corrected for wounding, and zero flow conditions after (Pfautsch et al. 2015), as well as sapwood properties from wood samples.

2.2.2 Quantifying Transpiration

For the MONASH trees, transpiration (L hr^{-1}) was estimated using the weighted average technique (Hatton et al. 1990) whereby sapwood area is separated into concentric rings and sap velocity measured at two depths are then multiplied by corresponding sapwood area. Since MORELAND trees were smaller, *E* was estimated as the product of sap velocity at one depth and all sapwood area.

2.3 The water balance

2.3.1 Quantifying stormwater retention

To quantify the volume of stormwater captured by each system, 0.5 m long capacitance water level sensors (Dataflow Systems Ltd., Christchurch, NZ) were installed in perforated PVC access tubes. Water level was recorded at 6 minute timesteps for both sites, and volume of stormwater captured (L) was calculated after Szota et al., (2019) as

$$Retention = (SA_{trench} \times \sum \Delta WL) \times p \quad \text{(Eq.1)}$$

Where SA_{Trench} is the surface area of the trench (MONASH: 6 m^2, MORELAND: 0.72 m^2), ΔWL is any positive change in water level during a rainfall event (mm) and *p* is the porosity of the gravel (MONASH: 0.4, MORELAND: 0.47).

2.3.2 Estimating the water balance

To assess the potential proportion of inflows that can be transpired by trees adjacent to SCMs relative to infiltrated stormwater, we estimate the water balance as

$$Q_{runoff} = Q_{intercepted} + Q_{Bypass} \quad \text{(Eq.2)}$$

Where Q_{runoff} is the product of rainfall (mm) and catchment area (m^2) and Q_{Bypass} is the volume of water bypassing the system, estimated as the difference between Q_{runoff} and *Retention* (Eq.1). $Q_{Intercepted}$ is the volume of stormwater captured and is described by

$$Q_{Intercepted} = Q_{Transpired} + \Delta Soil \quad \text{(Eq.3)}$$

Where *Transpiration* (L) is total tree water use, and $\Delta Soil$ is the change in soil water storage from intercepted stormwater, which can be positive (exfiltration, restoring surrounding soil moisture) or negative (transpiration, drawing from surrounding soil moisture).

3 RESULTS AND DISCUSSION

3.1 Tree size affects transpiration and its contribution to the water balance

The average volume of runoff intercepted per SCM at the MONASH site (946 L) was double that observed at the MORELAND site (460 L), yet, the proportion of runoff intercepted was not significantly different (a similar proportion of total runoff (12 to 14%), despite the small size of SCMs at the MORELAND site relative to their catchment area (Table 1). This is because flows into the MONASH systems were limited by inflow capacity, meaning the systems rarely filled to capacity, unlike the MORELAND SCMs. Transpiration was much higher per SCM at the MONASH site (1100 L $month^{-1}$), as would be expected for established trees, compared with 70 L $month^{-1}$ for establishing trees at the MORELAND site. This meant up to 30% of runoff could be transpired from an established tree adjacent to an SCM (Fig. 2B) and highlights the potential for trees to utilise large volumes of stormwater from SCMs. While other factors influence transpiration rates of trees, such as species and site characteristics, the difference in mean daily transpiration rate (L cm^{-2} of sapwood) between the MORELAND (0.196 L cm^{-2}, *Acer campestre*) and MONASH (0.217 L cm^{-2}, *Lophostemon confertus*) sites was small, supporting the assumption that tree size plays a larger role in the contribution of transpiration to the water balance.

3.2 Potential benefits of tree-based stormwater control measures

A key aim of harvesting stormwater in urban areas is to recover natural baseflow conditions by designing SCMS that combine infiltration and evapotranspiration of stormwater runoff. This study highlights the possible change in water balance outcomes over the life cycle of an SCM adjacent to a street tree. For SCMs adjacent to small, establishing trees, the primary benefit will be increased infiltration and groundwater recharge for intercepted stormwater (positive change in storage, Fig.2B). Over time, as the tree increases transpiration with size, the primary benefit will be evapotranspiration and use of captured stormwater (negative changes in storage, Fig.2B) that could allow greater retention in subsequent events, as well as supporting the growth and health of urban street trees and the ecosystem services they provide. Annually, change in storage will vary with tree size and phenology. In winter months, infiltration will likely comprise a greater proportion of the water balance of SCMs, especially for smaller or deciduous trees. Hence, ensuring systems are designed to limit waterlogging of trees that cannot utilise stormwater during this time will be particularly important. Integrating trees with stormwater management provides an opportunity to maximise the benefits of trees and SCMs in urban areas.

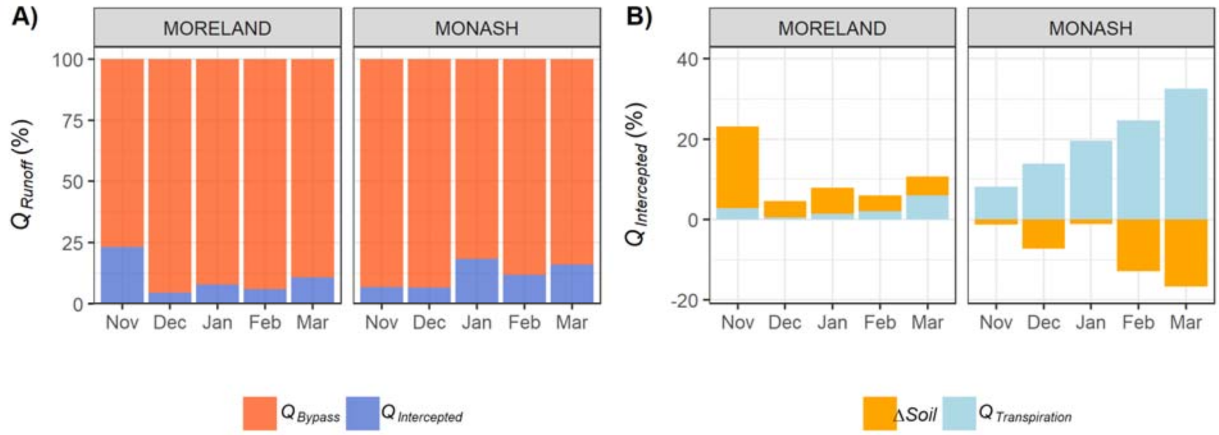

Figure 2: Partitioning of the water balance. A) The proportion of stormwater runoff that either bypasses (Q_{Bypass}) or is intercepted ($Q_{Intercepted}$) by the SCM. B) The proportion of runoff intercepted is balanced by transpiration ($Q_{Transpiration}$) and change in soil water storage (*ΔSoil*) An example of the proportion of intercepted stormwater that is transpired and contributes to increased soil moisture (positive *ΔSoil*) or where transpiration exceeds intercepted stormwater supported by a change in surrounding soil moisture (negative *ΔSoil)*

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