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The economic benefits of reductions in nitrogen loads from stormwater runoff by street trees

Mariana D. Baptista[a,*], Marco Amati[a], Tim D. Fletcher[b] and Matthew J. Burns[b]

[a] Centre for Urban Research, School of Global Urban and Social Studies RMIT University, Melbourne, Australia

[b] School of Ecosystem and Forest Sciences, Faculty of Science, University of Melbourne, Melbourne, Australia

*Corresponding author. E-mail: mariana.diasbaptista@rmit.edu.au

Abstract

It is increasingly recognised that urban trees can contribute to reducing stormwater runoff by intercepting and retaining a fraction of rainfall received. What is less studied is the translation of this to reduced pollutant loads being transferred to receiving streams, rivers, and water bodies. In this paper, we assess interception of two tree species (*Eucalyptus microcorys* and *Ulmus procera*) in an urban park. These data are used in simple water balance modelling to predict the environmental and economic benefit of reducing nitrogen loads to receiving waterways as a function of reduced runoff volume resulting from rainfall interception by urban trees on public land (21% of the catchment area). We use a highly urbanized catchment in Melbourne, Australia to demonstrate the impact of an urban forest dominated by deciduous trees, evergreen trees or a mixed tree canopy cover. We found that doubling the urban canopy cover in the catchment, while keeping the current mix ratio of deciduous and evergreen trees, could reduce annual runoff volume by 30 mm (92 $MLyr^{-1}$). Using the prescribed values that developers must pay the local water authority for nitrogen treatment as a condition of new development, we calculate that this would deliver a nitrogen load removal benefit of AUD$ 200/tree. If only deciduous trees are planted, the annual runoff reduction would decrease to 24 mm (73 $MLyr^{-1}$) and increases to 37 mm (112 $MLyr^{-1}$) if only evergreen trees are planted. This study highlights both the additional benefits of public street trees and the differences in deciduous and evergreen trees which should be accounted for by policy makers.

Key words: ecosystem service valuation, interception, nitrogen load, urban forest canopy cover, water storage capacity

Highlights

- Different scenarios of canopy expansion showed a greater runoff reduction when evergreen species are planted.
- The role of street tree planting in runoff and nitrogen load reduction will depend primarily on available space.
- An additional environmental and economic benefit of public trees should be accounted for by policy makers.

INTRODUCTION

Since the 1990s decision-makers in cities around the world have come to realise the benefits of green infrastructure; all green spaces, plants and designed vegetation systems within the urban landscape

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(Mell 2017). The result of this realisation has included efforts to vastly expand urban canopy cover in the hope that it will deliver benefits in public health (Ulmer *et al.* 2016), air pollution reduction (Vailshery *et al.* 2013), heat mitigation (Coutts et al. 2012) and stormwater retention, infiltration and evaporation (Berland *et al.* 2017).

It is well known that trees can have multiple benefits when looked at holistically as part of a blue-green system. Trees have benefits such as buffering extreme rainfall events by intercepting water and holding it on their leaf and branch surfaces. During rainfall, the tree canopy surfaces potentially intercept up to 26% of the rainfall and reduce runoff in an urban streetscape, depending on the species characteristics (Baptista *et al.* 2018). Consequently, increasing stormwater buffering capacity in the tree canopy could reduce the need to upgrade the capacity of conventional stormwater drainage systems and reduce the impacts of stormwater runoff on urban receiving waters. Although cost savings on storm water reduction by volume are highly contingent on individual context, awareness of these savings provides justification for the expense of planting and maintaining green infrastructure. For example, in Melbourne, Australia, the regional water authority (Melbourne Water) has budgeted more than AUD$700 M on projects to reduce flood risk and manage storm water quality and quantity over five years (Melbourne Water 2016).

As well as reducing the magnitude of stormwater discharge to receiving waters, thus potentially reducing channel degradation (Anim *et al.* 2018), ecosystem degradation (Walsh *et al.* 2005) and the magnitude of flood flows (Van Stan *et al.* 2014), trees can reduce the contribution of nitrogen loads (hereafter N-load) to receiving waters from urban stormwater runoff (Harris *et al.* 1996). Since the late 1980s there has been a growing awareness of the impacts of urbanization on diffuse sources of N-load entering major receiving waters, such as Chesapeake Bay in the USA (Galloway *et al.* 2003), or Port Phillip Bay in Melbourne, Australia. Port Phillip Bay is a semi-enclosed ecosystem adjacent to the City of Melbourne, and is sensitive to accumulation of nitrogen, increasing its risk of eutrophia (Murray & Parslow 1998). The Victorian Government has therefore enacted State Environmental Protection Policy that progressively sets lower targets for N-loads entering Port Phillip Bay, supported by an extensive management plan (Melbourne Water 2009). Currently the objective is 150–300 (μg/L) total-N and no more than 1,500–3,100 tonnes of nitrogen can enter the bay annually from surrounding waterways and the Western Treatment Plant (Victorian Government 2018). To fund works aimed at reducing N-loads from urban stormwater, Melbourne Water requires new residential developments to treat their nitrogen on-site, using techniques such as wetlands, swales and bioretention systems. In cases where the developer is unable to comply with this requirement, Melbourne Water charges the developer an up-front one-off nitrogen treatment fee of '$6,645/kg N (per kilogram of annual total nitrogen load) plus and an administration fee of 8.9%' (Melbourne Water 2019).

The City of Melbourne is a municipality that occupies the central business district (CBD) of Metropolitan Melbourne, Australia with catchments that flow into Port Phillip Bay. It currently employs a formula for calculating the amenity value of a tree on public land (e.g. a street tree) in the case where it has to be removed for private development. This consists of the size of the tree measured as diameter at breast height (DBH), a factor for the species, the aesthetics, the locality and the condition (City of Melbourne 2012a, 2012b). The cost of a large tree for replacement can be significant – e.g. ~$100,000 ($AUD) for a tree of 100 cm DBH.

Given this dual context of financial consequences regarding N-loads and the removal of trees, the City of Melbourne and the receiving water Port Phillip Bay make an ideal case study of blue-green policymaking in action. In this paper, we test scenarios of greening in the Elizabeth Street Catchment, an area of approximately 302 ha that is a mixture of residential and commercial high rise and low-rise residential (Figure 1). This study aims to test different scenarios to understand the contribution of trees to runoff reduction. From these results, a simple model predicts the N-load savings in cost terms for this policy and legislative environment.

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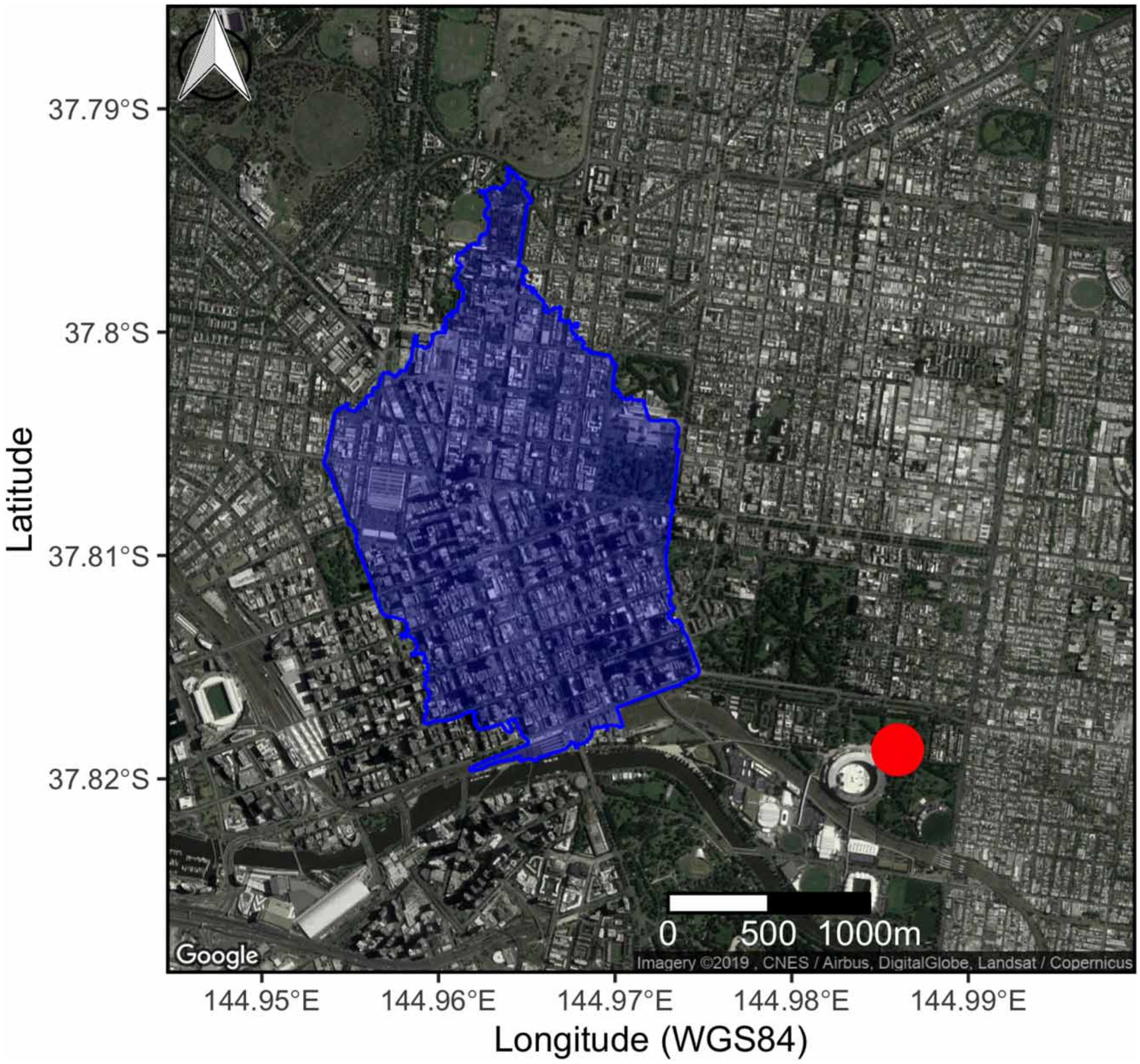

Figure 1 | Map of the Elizabeth St Catchment (blue zone) and treed park (red circle) where tree interception was measured in Melbourne, Australia.

METHODS

Experimental field data

An experiment to understand the amount of water captured by trees was conducted at Yarra Park, Melbourne, Australia. Melbourne historical climate data shows annual mean maximum and minimum temperatures ranging from 19.8 °C to 9.6 °C, while the average annual precipitation (1970–2016) is 534.5 mm (Bureau of Meteorology 2016). Melbourne is sited in a region of temperate climate (Cfb) according to the Köppen–Geiger classification (Peel *et al.* 2007), which means that all four seasons are distinct, with winter mostly humid and cold, and summer hot and dry. The pattern of rainfall is fairly uniform throughout the year, but most rainy days occur during late-winter and spring (Agriculture Victoria 2019).

Yarra Park is a private urban park that is open to the public. It is located to the south-east of the Melbourne central business district (CBD), comprises an area of approximately 28 hectares and houses the Melbourne Cricket Ground (MCG). Trees cover approximately 45% of the total park area (12.6 hectares), including 1,212 trees of 58 different species and cultivars (Yarra Park Tree Strategy 2013).

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Species description

Two species were measured for this study: *Eucalyptus microcorys* (Tallowwood) and *Ulmus procera* (English Elm). *E. microcorys* is a broad-leaved evergreen species, originating from the Queensland and New South Wales regions in Australia (Atlas of Living Australia 2018). *U. procera* is a broad-leaved deciduous species originating from Europe (Lefoe 2008). Two trees of each species were selected. These trees provide contrasting canopy characteristics and phenology, and the individuals measured were isolated canopy, mature age trees that were logistically safe to access.

Tree height, diameter at breast height (DBH) and canopy cover were remotely estimated through Light Detection and Ranging (LiDAR) data collected by a drone in January 2017. PAI values were estimated using the digital cover photography method, applying the coefficient of extinction based on the literature (Macfarlane *et al.* 2007).

Throughfall collection

The data were collected in an event-based interval whilst all tree species were in leaf between January and April 2017. Throughfall was measured for the same rainfall events under two trees of different species (Group 1 and 2) using four tipping rain gauge buckets per tree (King & Harrison 1998; Park & Cameron 2008). The tipping rainfall gauges with a datalogger (Rain Collector II, Davis Instruments, California, US; and Odyssey Data Logger, Dataflow Systems, Christchurch, NZ) were placed 1.5 m from the trunk in each cardinal compass direction and were levelled to a horizontal plane (Figure 2). Rainfall gauges were removed from the park after the rainfall event had ceased. The collecting points were marked with a wooden stake in the ground, ensuring that data were collected at the same points during different rainfall events.

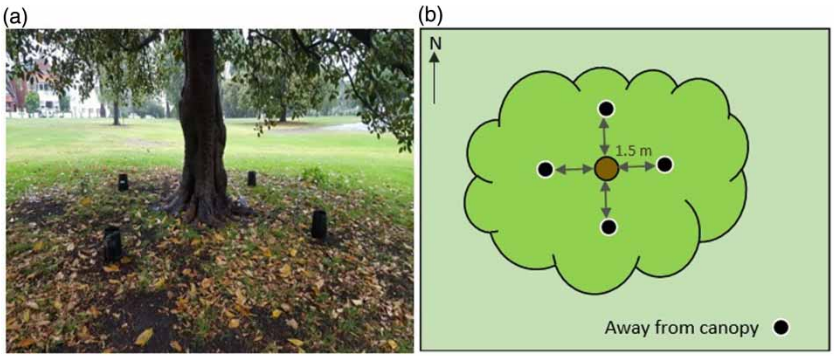

Figure 2 | (a) Photo of tipping buckets placed around the central stem; (b) Sketch of arrangement of tipping buckets around central tree stem, indicating placement at 1.5 m from the stem (top view).

Two control tipping rain gauges were placed away from the tree canopies to measure the total amount of rainfall during the event, or gross precipitation. Throughfall was calculated as an average of the four rainfall gauges under-canopy. Canopy interception was calculated as the difference between gross precipitation and throughfall (Equation (1)).

$$I = P - T \quad (1)$$

where, I = interception; P = gross precipitation; T = throughfall.

Rainfall events were included in this analysis when gross precipitation for a single event was ≥2 mm and there was a minimum of four hours without precipitation before or after that rainfall

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event. This minimum amount of rain guarantees that throughfall occurs. Additionally, the 4 hours interval allows trees to dry and restore the maximum capacity to store water, minimising errors (Asadian & Weiler 2009). Supporting climate data, such as average wind speed and direction, temperature and humidity, were acquired from the Melbourne (Olympic Park) weather station (ID: 086338; Lat: −37.83; Lon: 144.98; Height: 7.53 m) located 1 km from the study area (Bureau of Meteorology 2017).

The collected throughfall data were used to produce linear models per species as a function of the event gross rainfall. The linear models were built using the 'lm' function (least squares regression) in the R software package. These interception models were used to predict throughfall for a given daily rainfall. While the line of best fit was used for these predictions, we did test how sensitive the final outputs were at the 95% confidence level.

Predicted scenarios

The scenarios were based on the Elizabeth Street Catchment in Melbourne, Australia (Figure 1), and targeted tree canopy on publicly managed impervious land. The precinct is built over a small stream that runs in to the Yarra River. Since its construction (in the 1860s), the street has been flooded numerous times during the last 160 years, most recently in 2010 (News 2017). The catchment drains 302 ha of mostly impervious land and constitutes a major hub of commerce in Melbourne. The local municipality is responsible for managing a large proportion of the catchment (115 ha or 38.2%), most of which is covered by impervious surfaces (82 ha or 71% of the area managed by the municipality). The combination of a high density of impermeable surfaces and the low point location of the catchment makes the water in this zone prone to receive more pollution from nearby areas. Additionally, the catchment is categorised as being at the highest level of flood risk (Extreme) by the local water authority (City of Melbourne 2015). The current level of canopy cover on public land is 25 ha (21.8%), with most trees overhanging impervious surfaces (18 ha). Within this current scenario, the City of Melbourne has prioritised green initiatives to manage stormwater, including an increase in canopy cover to 40% on public land across the catchment by 2040 (City of Melbourne 2015).

We used simple water balance modelling (e.g. Equation (2)) to firstly predict the amount of impervious runoff based on the current level of canopy cover on public land (but only trees covering hard surfaces):

$$R_c = R_i/103 \times [(A_i - CC_i) \times 104] + (Tf_d/103) \times [(CC_i \times 0.80) \times 104] + [(Tf_e/103) \times (CC_i \times 0.20) \times 104] \quad (2)$$

where,

R_c, current impervious runoff (m3 day^{-1})
R_i, impervious surface runoff (mm day^{-1})
A_i, area of impermeable surface (ha)
CC_i, area of canopy cover over public impervious surfaces (ha)
Tf_d, throughfall under deciduous trees (mm day^{-1})
Tf_e, throughfall under evergreen trees (mm day^{-1}).

Daily N-loads were predicted simply by multiplying the impervious runoff values by a range of total nitrogen (TN) concentrations presented in Duncan (1995), where mean 2.09 mgL^{-1}, lower value 1.58 mgL^{-1} and upper value 2.75 mgL^{-1}. In other words, we did not attempt to account for the complexities of build-up and wash-off processes, nor of possible first flush phenomena (Nazahiyah *et al.* 2007), given the range, complexity and spatio-temporal variability of factors that drive such processes (Perera *et al.* 2019). Similarly, the predictions did not attempt to account for potential impacts of tree canopy on pollutant concentrations.

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Scenarios were modelled with the amount of canopy cover expanded by 20 ha of: (a) deciduous trees, (b) evergreen trees, or (c) an equal mix of both. Stormwater quality characteristics, as described in detail previously, were used to convert the runoff predictions to N-loads, which were then used to quantify an economic benefit of the trees. Details on these steps are described below.

No tree scenario

In order to quantify the benefit of the current level of canopy cover, N-load predictions based on the 'no tree' case were required. Such predictions were made by firstly sourcing 6-min rainfall data (units = mm) for the city based on a reference year of 1959 (annual rainfall of 655 mm; similar to the long-term Melbourne mean annual rainfall of 648 mm). The sub-daily rainfall data was aggregated to a daily time-step and then converted to impervious runoff using an initial loss value of 1 mm day^{-1} (Walsh *et al.* 2012). The daily time-series of impervious runoff depth was multiplied by the area of impervious surface covering publicly managed land (82 ha) which yielded a time-series of impervious runoff in units of m^3. The daily pollutant-load values were aggregated to annual and this represented the annual mass of total nitrogen generated from all impervious surfaces within public land in the absence of trees.

Current scenario

This scenario reflected impervious runoff and N-load from all impervious surfaces within public land, based on the current level of tree canopy cover. Thus, the difference between this scenario and the 'no tree' one was the retention of water and pollutants afforded by the canopy of the existing trees. The hydrological calculations for this scenario were similar to the 'no tree' scenario but made use of the experimental throughfall observations.

The first step here was to predict runoff and N-load from the existing canopy cover which overhangs the study site's impervious surfaces (18 ha). The existing canopy cover is made up of 80% deciduous trees, with the remainder evergreens. Throughfall collected at the park for the deciduous tree *U. procera* and the evergreen tree *E. microcorys* was plotted as a function of the gross rainfall of each event to build linear models. The daily time-series of rainfall and the linear models were used to predict throughfall for the two tree species. We assumed the throughfall predictions for *U. procera* as representative for all deciduous trees in the study area. And similarly, the plotted throughfall predictions for *E. microcorys* were regarded as representative for the evergreen trees. Since deciduous trees drop their leaves in the colder months, we set predicted throughfall for these trees as a large fraction of rainfall (90%; Baptista *et al.* 2018) across May–September. A snapshot of these predictions in shown in Figure 3.

Finally, we did not account for interception chemistry and assumed that throughfall landing on the impervious surface below was subject to the same initial loss described earlier (1 mm day^{-1}; Walsh *et al.* 2012). The resultant daily time-series of remaining water for each of the tree types was multiplied by the relevant canopy coverage to yield runoff in units of m^3. These runoff predictions were then added to a daily time-series of runoff based on the non-shaded impervious surfaces in the study area. This final time-series represented impervious runoff from all impervious surfaces within public land based on the current level of canopy cover. Daily N-loads for this scenario were obtained by multiplying runoff by the range of TN concentrations and then aggregated to an annual mass.

Canopy expansion

Three canopy expansion scenarios considered (a) deciduous (*Ulmus procera*) trees, (b) evergreen (*Eucalyptus microcorys*) trees, or (c) an equal (50:50) mix of both. The approach to predict runoff

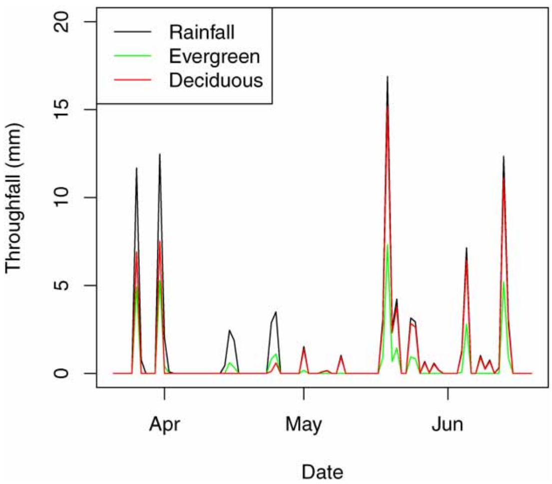

Figure 3 | Throughfall predictions for evergreen and deciduous trees used in this study. During the warmer months (i.e. prior to May), a large fraction of rainfall is intercepted by the trees. When the deciduous trees drop their leaves (i.e. from May), they only intercept a very small fraction of rainfall (10%).

and N-loads for these scenarios was the same as for the 'current scenario', albeit with an increase of 20 ha in the area of public impervious surfaces covered by tree canopy.

Economic benefit

After calculating the avoided annual N-loads for each scenario, the values were converted to an economic benefit using the estimated cost of stormwater treatment calculated by the local water authority. Melbourne Water charges developers a one-off up-front payment for a nitrogen treatment fee of: '$6,645/kg N (per kilogram of annual total nitrogen load) plus and administration fee of 8.9%' (Melbourne Water 2019). This is the cost needed to build a 'standard' stormwater treatment wetland, which could remove 1 kg of N per year. Therefore, this one-off avoided capital cost for nitrogen treatment was calculated by multiplying the annual N-loads (kg) for each scenario by the monetary value for treatment ($AUD).

RESULTS

Canopy measurements

Measurements of Yarra Park trees showed similar values of DBH for all *U. procera* (UP) trees and E. *microcorys* (EM) (Table 1). The projected canopy area ranged between 180.5 m^2 for an *U. procera* and 246.5 m^2 for an E. *microcorys*. Canopy cover ranged between 0.97 for an *U. procera*, to 0.77 for an E. *microcorys*.

Table 1 | Description of measured diameter at breast height (DBH), height (H), canopy area (CA), canopy volume (CV), plant area index (PAI), literature-based extinction coefficient (k) and calculated canopy cover faction (C) for trees in Yarra Park

Tree ID	Species	DBH (m)	Height (m)	PAI	Extinction coefficient (k)	Canopy cover
EM1	*Eucalyptus microcorys*	0.99	19.7	8.76	0.25	0.89
EM2	*Eucalyptus microcorys*	0.76	16.7	5.84	0.25	0.77
UP1	*Ulmus procera*	0.73	13.2	6.49	0.5	0.96
UP2	*Ulmus procera*	0.74	13.5	7.36	0.5	0.97

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Rainfall event description

From January 2017 to April 2017, 9 discrete rainfall events with more than 2 mm depth were considered in this analysis (Table 2). Figure 4 shows the data for all rainy days during the sampling period gathered from the closest weather station (Melbourne Olympic Park station).

Table 2 | Rainfall characterization and environmental conditions for each event measured in 2017

Event	Date	Tree group	Gross rainfall (mm)	Duration (h)	Intensity (mm/h)	Time since last rainfall (h)	Average temperature (°C)	Average Wind speed (km/h)	Predominant wind direction
1	20-Jan	1	22.8	8.0	2.9	> 24	17.3	9.5	S
2	20-Feb	1	3.9	9.0	0.4	> 24	13.3	10.9	NW
3	20-Mar	2	2.4	1.9	1.3	> 24	22.6	7.6	SSW
4	21-Mar	2	2.2	1.6	1.4	6.0	20.2	2.5	NE
5	22-Mar	2	9.0	0.6	15.5	6.5	23.2	6.8	NE
6	27-Mar	1	5.8	3.0	1.9	> 24	19.2	13.4	NNW
7	28-Mar	2	3.4	1.9	1.8	> 24	11.1	7.7	SSW
8	9-Apr	2	7.6	4.0	1.9	> 24	18.1	17.1	N
9	10-Apr	2	14.4	17.8	0.8	9.0	11.7	21.2	WSW

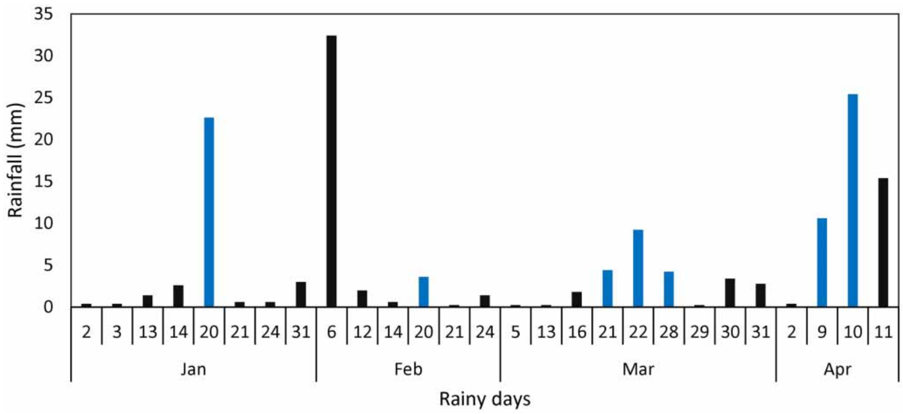

Figure 4 | The total rainfall per day during the sampling period (02/01/2017–11/04/2017). Blue columns represent the days when throughfall data were collected in the park. Rainfall data gathered from the nearest weather station (Melbourne Olympic Park; ID: 086338; Lat: −37.83; Lon: 144.98; Height: 7.53 m).

A total of 71.5 mm of rainfall was collected during an overall period of 47.7 hours. The rainfall intensity ranged from 0.4 to 15.5 mm/h and the average rainfall intensity was 3.2 mm/h. Air temperature ranged from 11.1 to 23.2 °C. The highest average wind speed was recorded as 21.2 km/h during event 9.

The correlation between collected throughfall and gross rainfall data for each species showed a linear relationship (Figure 5). These linear models were used to predict throughfall for a given daily rainfall.

Predicted scenarios

We predicted that the current level of canopy coverage in the catchment reduces the amount of runoff delivered to the receiving water by ~9% (Table 3) in comparison to the scenario without any trees.

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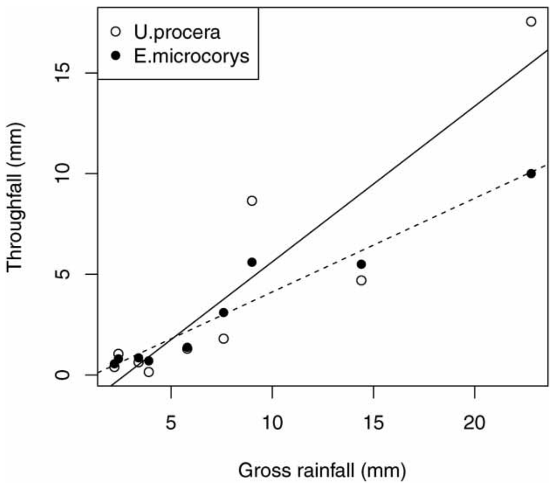

Figure 5 | Linear correlation between gross rainfall and throughfall for two studied species: E. *microcorys* (dashed line; $R^2 = 0.94$ and slope estimate = 0.47 [0.36–0.57; 95% confidence interval]) and *U. procera* (solid line; $R^2 = 0.83$ and slope estimate = 0.77 [0.46–1.09; 95% confidence interval]).

Table 3 | The water quality and economic benefit of urban canopy cover based on current levels as well as under future expansion scenarios

Scenario	Annual runoff (ML)	Avoided annual runoff (ML)	Avoided annual runoff (mm)	Annual N-load (kg)	Avoided annual N-load (kg)	Avoided capital cost ($AUD*$10^3$)
No trees	447	–	–	934 (706–1,229)	–	–
Current canopy	408	39	13	853 (645–1,122)	81 (61–107)	586 (441–774)
Canopy expansion all evergreen trees	335	112	37	701 (530–922)	233 (176–307)	1,686 (1,274–2,222)
Canopy expansion all deciduous trees	374	73	24	781 (591–1,028)	152 (115–201)	1,100 (832–1,455)
Canopy expansion an equal mix of deciduous and evergreen trees	355	92	30	741 (560–975)	193 (146–254)	1,397 (1,057–1,838)

Expansion of the urban canopy cover could result in an even greater reduction in runoff from publicly managed impervious ground surfaces of up to 25% when broad-leaved evergreen tree canopy is doubled, in comparison to the 'no tree' scenario (Table 3). These reductions in runoff volume translated to tangible benefits in terms of annual N-load avoidance (Figure 6 and Table 3). The avoided capital cost provided by the urban canopy cover in terms of N-load avoidance amounts to ~$600,000 ($AUD) today. Doubling the current level of canopy cover could accrue an additional ~1,000,000 ($AUD) of benefit. Note that sensitivity testing of the predicted throughfall values revealed minor differences in the final outputs (<10%) at the 95% confidence level (see Supplementary Material).

DISCUSSION

Runoff reduction in different scenarios of canopy cover expansion

This study presents a simple canopy interception model that uses two linear functions to estimate canopy interception by typical deciduous and evergreen street trees. There are other more complex

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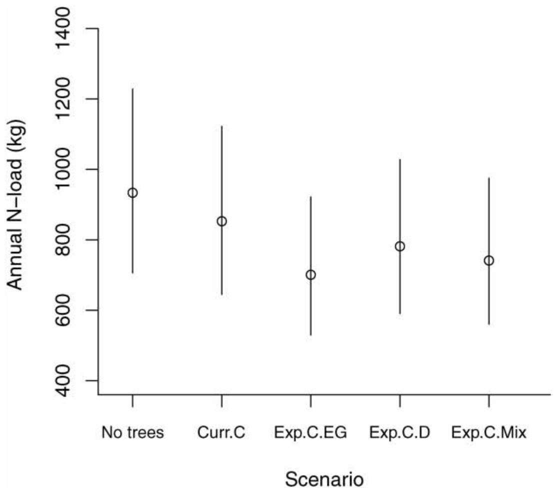

Figure 6 | Predicted range of annual N-load from the impervious parts of public land within the Elizabeth Street Catchment. Trees covering hard surfaces provide some N-load avoidance through interception (Curr.C), with further reductions possible with canopy expansion using only evergreens (Exp. C. EG), only deciduous (Exp. C. D) or equal mix of deciduous and evergreen trees (Exp/ C. Mix).

models that attempt to partition different pathways for intercepted rainfall by taking into account the different structure of isolated, open-grown trees and the environmental micro-climate conditions in the urban landscape (Rutter *et al.* 1970; Gash *et al.* 1995; Xiao *et al.* 2000; Asadian & Weiler 2009). One of the most detailed and complex urban tree hydrology models was developed by Xiao *et al.* (2000), including stemflow, and throughfall, and input data relating to leaf angle, leaf area index, stem/branch area index, and leaf surface water storage capacity. However, this complex mechanistic model was still most sensitive to input data on rainfall depth (mm) and leaf surface water storage capacity, both of which are considered in the simple model presented in our study. Similarly, a popular urban tree interception model developed by Gash *et al.* (1995) has been shown to be most sensitive to rainfall rates, as well as subsequent evaporation rates (Huang *et al.* 2017). Even though our hydrologic model is simple, it is able to account for the key variables determining runoff reduction by trees; canopy water storage capacity and rainfall amount, so we have confidence that the scenario estimates of runoff reduction are meaningful.

To fully understand and predict the potential of street trees to influence urban catchment hydrology it would be important to not only simulate canopy interception but also the use of retained, stored or infiltrated stormwater through tree transpiration (Berland *et al.* 2017; Kuehler *et al.* 2017; Grey *et al.* 2018a). Urban surface–atmosphere transfer models attempt to consider both the urban energy and the urban water balance. An early urban evaporation–interception model was the 'single-source urban evapotranspiration-interception scheme' (SUES) (Grimmond & Oke 1991). The SUES model has not been used to simulate urban tree interception–evaporation, but Mitchell *et al.* (2008) has used SUES to simulate green infrastructure systems and estimated that stormwater runoff could be reduced by 33%, and evapotranspiration increased by 14%. However, many surface–atmosphere transfer models often use a single static function to estimate gross rainfall reduction, so may provide less predictive power of canopy interception than simple hydrologic models such as the one presented in our study.

Rodriguez *et al.* (2008) simulated 10 years of catchment rainfall, runoff, soil moisture and stream discharge using a hydrologic model (URBS-MO) and was able to predict that tree canopies reduced gross rainfall by 2.7%. In contrast, transpiration (tree and grass) in the same catchment represented a return of 43.5% of gross rainfall back to the atmosphere. However, it must be recognised that this low-density, high-green space, suburban catchment simulated by Rodriguez is very different to the high-density, sparse green space of the Elizabeth Street catchment in the City of Melbourne. Rainfall

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infiltration in the Elizabeth Street catchment will be negligible due to the high impervious cover, so the importance of tree-grass transpiration will be far less, and probably comparable to the percentage of canopy interception.

Wang *et al.* (2008) used the UFORE-hydro model to simulate runoff reduction of only 3.4% when there were 40% tree canopy cover above impervious ground surfaces within an urban catchment. Zölch *et al.* (2017) used the MIKE SHE model to simulate the role of urban trees and green roofs in the hydrology of a small inner-city neighbourhood. Even when trees were planted at a high stem density, and achieved a canopy cover of 25%, the reduction in runoff from canopy interception was only 2.7%. These two studies predict far less runoff reduction from realistic tree canopy scenarios as compared to the 9% runoff reduction predicted in our study under current canopy cover, increasing to 20% under doubled tree canopy cover. These differences may be attributed to the use of canopy cover as an estimate of potential surface area for water store in the canopy. Using canopy cover as a percentage may hide the complexity of interception processes in urban areas (Holder & Gibbes 2016; Baptista *et al.* 2018).

Kirnbauer *et al.* (2013) used a simplified version of the i-Tree Hydro model to assess the hydrologic benefits of trees over 7 years from planting. Their results demonstrated that the canopy reduced gross rainfall from 6.5% up to 27% of the total rainfall that falls onto the crown across the 7 years studied, for broad-leaf deciduous tree stands (*Ginko biloba*, *Platanus* × *acerifolia*, *Acer saccharinum*, and *Liquidambar styraciflua*).

Research into urban runoff reduction through vegetation strategies has generally focused upon green roofs, biofilters, and engineered wetlands (Berland *et al.* 2017; Meerow & Newell 2017). Many cities still do not consider urban green infrastructure, let alone urban trees, in their development of runoff mitigation strategies (Dolowitz *et al.* 2018), while other cities are embracing the potential of the urban forest and novel green infrastructure and stormwater control measures (SCMs) to reduce catchment runoff (Gotsch *et al.* 2018).

Ultimately, returning the water balance towards its pre-development level will only be possible using a combination of vegetation strategies and projects which harvest substantial volumes of stormwater. The latter is particularly important, as modelling work has shown that mimicking the natural water balance at small scale requires significant water consumption, for example through rainwater tanks connected to end-uses which consume quantities of water and regularly (e.g. toilet flushing, clothes washing, hot water usage, etc.) (Burns *et al.* 2014). Achieving high levels of stormwater harvesting is theoretically easiest in cities where the demand for potable water alternatives is high relative to the impervious footprint (which, ironically, will be high-density urban areas with multi-storey apartment buildings). Vegetation plays an important complementary role, through its creation of evapotranspirative 'demand'.

Nitrogen load avoidance

Our results suggest that urban canopy cover in highly urban areas provides only a small benefit in terms of N-load avoidance by interception. The main reason for this is because the trees intercept a small fraction of the overall volume of rain falling on the catchment. Additionally, analyses of throughfall water quality have shown increases in N-loads (Xiao & McPherson 2011). Air pollution deposition on leaves and branches has been described as a major factor influencing the quality of water after it leaches through the canopy surfaces in urban areas. Our results do not account for the N-amount that has been stored on leaves and branches as it is carried out through the rainfall to the ground, which may decrease the economic benefit in terms of N-load avoidance. Nor does it account for bacterial activity which returns N to the atmosphere. There is thus the potential to expand this type of work in future to incorporate empirically derived estimates of canopy interception on pollutant *concentrations*, although doing so would need sufficient data for each of the species being

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considered. Furthermore, it would be worthwhile to undertake this analysis in a given area, using locally available high-quality data on nitrogen concentrations and loads (e.g. Lucke *et al.* 2018).

On the other hand, studies have shown the importance of trees on redirecting stormwater via stemflow in urban areas (Schooling & Carlyle-Moses 2015). Following the water path throughout the canopy surfaces, part of the nitrogen leaching from the tree's surfaces may infiltrate into the surrounding soil. Increasing and improving the available permeable area around the tree roots may boost infiltration (Grey *et al.* 2018b), and consequently the filtration of nutrients in urban areas.

Complementary green infrastructure measures – e.g. biofilters and green roofs – which drain both private and public land, will be required for substantial N-load reductions. That said, urban trees provide many benefits which other types of green infrastructure simply do not (e.g. considerable shading).

Economic benefits of runoff reduction through N-load avoidance

Valuing the economic benefits provided by trees is essential as it allows them to be quantitatively compared against other infrastructures that have well established mechanisms of valuation. This study found that doubling the urban canopy cover in the catchment keeping the current mix ratio of deciduous and evergreen trees could reduce annual runoff volume by 30 mm. Using the values that developers must pay the local water company for nitrogen treatment we calculate that this would deliver an N-load removal benefit of $AUD 200/tree. If only deciduous trees are planted the runoff reduction would decrease to 24 mm (~$AUD 157/tree) and increase to 37 mm (~AUD$ 243/tree) if only evergreen trees are planted.

Many studies have attempted to evaluate the economic benefits of green infrastructure to runoff reduction in urban areas. Zhang *et al.* (2012) calculated the economic benefit of green areas for runoff reduction in Beijing based on the costs for rainwater storage in a reservoir plus services for water quality management, which was considered US$ 1.28/ m^3 in 2009. The economic value of rainwater-runoff reduction is equal to US$ 3.2 thousand dollars per hectare, and an estimated total economic benefit of approximately US$ 196 million.

McPherson *et al.* (2011) assessed the benefits of planting one million trees for reducing runoff in the city of Los Angeles. They based their calculations on the annual costs for managing water quality and controlling flooding (approximately US$ 1.90 per m^3). That indicates a benefit of US$ 97.4 M in a high-mortality scenario and up to US$ 153.1 M in a low-mortality scenario and an average benefit of US$ 3.58/tree/year.

While the City of Melbourne currently calculates the value of a street tree at ~$100,000 for a 100 cm DBH tree, the Ecological Services Value is calculated using the i-Tree model. This in turn only calculates the benefits of runoff reduction from trees based on 'yearly avoided runoff attributed to trees summarized by tree species or strata' (i-Tree Eco Manual, https://www.itreetools.org). Our study suggests that this figure could be augmented by a 'blue-green' flat-rate of N-load reduction per tree of ~AUD$170 in the Elizabeth Street catchment for many years until a replacement tree can be grown in the same place, based on the current number of street trees in the catchment (~3,500) and calculated economic benefit on N-load reduction (~$AUD 600,000).

CONCLUSION

This study combined field work with simple hydrologic models to calculate runoff reduction in trees with modelling of rainfall events to understand the economic benefits of street trees on N-load reduction. Runoff reduction was calculated through an empirically derived canopy interception model that uses two linear functions to estimate canopy interception by typical deciduous and evergreen street trees. Different scenarios of canopy expansion showed a greater runoff reduction when

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evergreen species are planted. This difference is a result of the decrease in storage capacity during winter days, when deciduous trees lose their leaves.

Runoff reduction was translated into reductions in nitrogen loads. This has allowed us to calculate the economic benefit of trees using the cost of urban stormwater treatment for nitrogen removal in Melbourne. Understanding the economic benefits provided by trees is fundamental to establish policies for stormwater management and allow planners to compare this benefit with other infrastructures that have well established mechanisms of valuation.

The work has two important policy implications. Firstly, the role of street tree planting in runoff and nitrogen load reduction will depend primarily on available space. In such a context, city planners should continue to invest in a suite of mechanisms that reduce the stormwater flows from hard infrastructure such as green roofs and rainwater tanks, along with investment in tree planting. In suburban areas where tree canopy can be expanded street, the role of trees will be proportionally larger. Finally, our work highlights that an additional environmental and economic benefit of public trees should be accounted for by policy makers.

Future research could benefit from applying this approach for predicting runoff reduction from throughfall or for alternative approaches. This prediction model could be compared to others and further refined, which may be a promising approach to incorporate empirically derived estimates of canopy interception on pollutant concentrations, for example.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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