

Quantifying the restoration of evapotranspiration and groundwater recharge by vegetated infiltration systems

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ABSTRACT

Infiltration-based source-control technologies are increasingly used in urban stormwater management in an attempt to restore pre-development catchment hydrology. To better assess the potential of infiltration systems to restore both the subsurface flow and the evapotranspiration in a catchment, information is needed about the fate of infiltrated water. To investigate this aspect, an experiment was set up to monitor the soil moisture surrounding a vegetated infiltration system ('raingarden'). The proposed methodology allows partitioning the volume of exfiltrated water between the deep and shallow soil layers of surrounding soils, with the latter volume being hypothesised as available for evapotranspiration. Preliminary results show that: i) less than 3% of the influent water is evapotranspired from the raingarden surface area itself; ii) the heavy clay soil within the lower part of the soil profile significantly limited exfiltration, meaning that most of the water (at least 70%) is exfiltrated into shallow layers. This provides opportunity for water to be later evapotranspired by surrounding vegetation. However, due to the absence of water stress during the studied period, the evapotranspiration from the surrounding soils was not significantly altered by the raingarden, such that the infiltrated water effectively recharged groundwater. The study has implications for the design of stormwater management strategies which aim to reduce the stormwater runoff volume and restore baseflows lost as a result of urbanization.

KEYWORDS

Evapotranspiration; infiltration system; soil moisture; water balance

INTRODUCTION

The degradation of urban streams is partly due to modification of the natural catchment hydrology, including an increase in surface runoff, with a corresponding reduction in evapotranspiration (ET) and infiltration-fed baseflows (Paul and Meyer 2001). Infiltration-based source-control technologies are often applied to mitigate these detrimental effects, by emulating natural infiltration and ET. They include a wide range of techniques such as bio-filtration cells (also known as 'raingardens'), infiltration trenches and swales. Modelling their impacts on ET and groundwater recharge is crucial for designing and assessing stormwater management strategies that aim to restore catchment hydrology. Such modeling can inform the optimal spatial distribution of these systems, along with design configurations to maximize infiltration or ET, depending on the objectives for the catchment. Various attempts to represent these catchment-scale effects have been made via semi-distributed reservoir-

based models (Göbel et al. 2004; Shuster et al. 2007; Elliott et al. 2010). This approach strongly relies on being able to represent the water balance of the systems, since the global contribution (to the catchment ET flux or subsurface flow) is a function of the contributions by the individual systems.

However, little information is available on the ‘total’ water budget of infiltration systems, i.e. one that quantifies water fluxes not only within the system itself but considers fluxes within the surrounding environment. Often, studies focus on the partitioning between ET, infiltration and outflow (if any), without taking into account the fate of the exfiltrated water (Holman-Dodds et al. 2003; Li et al. 2009; Palhegyi 2010). This omission may be critical in the case of low conductivity soils, where the exfiltrated water is likely to be retained and evapotranspired by surrounding vegetation (rather than seeping down to recharge the groundwater). To investigate this idea, we conducted a field experiment to partition the filtered water from a raingarden into ET and deep seepage. In addition to the monitoring of inflow and outflow from the raingarden, the analysis of moisture in the surrounding soils allows a better understanding of the total water budget of the raingarden. This article presents the preliminary results from the experiment, showing that most of the water is exfiltrated in the shallow layers, meaning that the evapotranspiration of much of the exfiltrated water is possible.

METHODS

Experimental set-up

The experimental site was a raingarden built in 2008 in a private property of Mount Evelyn (40 km from Melbourne, Australia). The infiltration system is one metre deep, made up of 450 mm of loamy sand overlying a 450 mm drainage layer of scoria (a volcanic gravel with a porosity of around 50-60%), with two 50 mm transition layers (course sand and fine gravel) in between the loamy sand and scoria. Its area is 10.1 m², with a length of 8.4 m and width of 1.2 m. It thus represents 3.1 % of its 321 m² impervious catchment area, but it also receives occasional overflow from a 5.5 m² raingarden that drains a 28 m² roof area. Its total perimeter is 19.2 m, with one side (8.4 m) of the system lined with a double layer of LDPE plastic to prevent water exfiltration towards the nearby swimming pool and house. It does not feature an underdrain so that losses occur by ET and exfiltration only.

The monitoring of the raingarden includes a tipping bucket rain gauge (Envirodata RG20) and water level and overflow probes (Odyssey capacitance water level loggers) which were installed in May 2008 to estimate the inflow, exfiltration and ET fluxes from the raingarden on a 5 min-time step. Additional sensors were installed in December 2010 and January 2011 to estimate the impact of the raingarden on surrounding soils, i.e. to partition the amount of

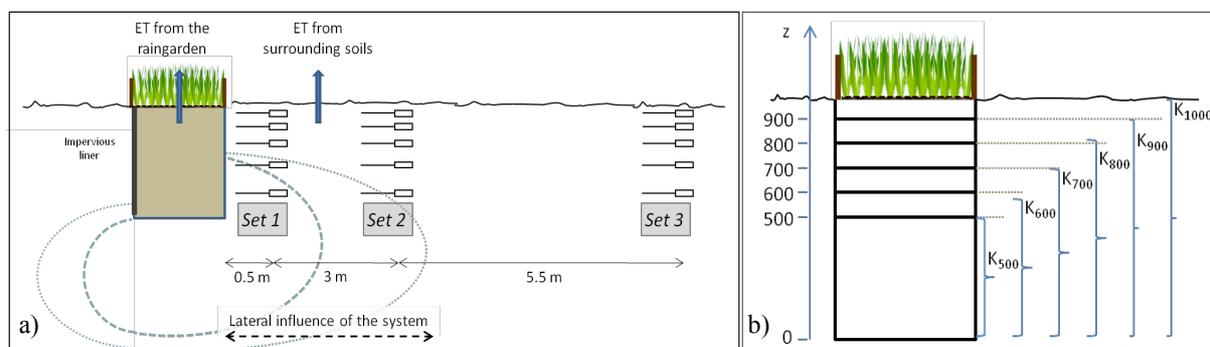


Figure 1. a) Schematic of the experimental set-up involving three sets of five soil moisture probes to investigate the influence of the raingarden on surrounding soils; b) Discretisation of the surrounding soil in layers to calculate exfiltration from the raingarden.

exfiltrated water between ET and deep infiltration. Moisture sensors (Campbell Scientific CS616) were thus installed in the surrounding soils in three sets of five buried at depths of 10, 20, 32, 60 and 85cm (Figure 1a). Each of the three sets is representative of a given distance from the trench (namely 0.5 m, 3.5 m and 9 m), the furthest one being used as a reference (i.e. soil not impacted by the raingarden). Data are collected to a Campbell Scientific CR800 datalogger and calibrated according to a laboratory-derived curve. Finally, to calculate potential ET (PET) additional weather station components were added to record air temperature and humidity (Campbell Scientific HMP45C), soil temperature (Pt 385 RTD) at 10 and 40 cm deep, wind speed (03002-L RM Young) and solar radiation (Campbell Scientific LP02). Data for the moisture sensors and the weather station are recorded at a 30 minute time step.

Hydraulic behaviour of the raingarden

To characterize the hydraulic behavior of the raingarden, a water balance was calculated as follows, with values recorded on a monthly basis.

Inflow. Inflow calculation was based on the volume of effective rain falling on the 321 m² catchment and the outflow from the small raingarden draining a 28 m² roof area. Initial loss from the roof was set to 0.6 mm and the rain from events less than 0.6 mm was assumed to be totally evaporated after 5 hours of dry weather. The small raingarden outflow was modeled with the MUSIC software (eWater CRC 2009), using a 6-minute time step and was (due to its large storage) found to contribute < 0.07% of the total inflow to the main raingarden.

Exfiltration. In order to separate ET from exfiltration, a semi-automatic filter was developed to measure night-time water level drawdown rates (from 7pm to 7am) for all dry periods from January to December 2009. The 205 measurements were grouped into 100 mm-thick layers (except for the first 500mm layer: Figure 1b). An average hydraulic conductivity K_i was calculated for the surrounding soil layer by solving the following equation expressing the mass balance for an infinitesimally narrow layer, being equal to the volume exfiltrated (with the assumption that no ET occurs during night-time):

$$\eta A_{rg} dh = K_i \times \left(h \frac{l_{rg}}{2} + A_{rg} \right) dt$$

where η is the porosity of the layer in the raingarden; A_{rg} and l_{rg} the area (10.1 m²) and unlined perimeter (10.8 m), respectively, of the raingarden; h is the water level (m); and K_i the equivalent hydraulic conductivity (m s⁻¹).

To account for the dependency of K_i on soil moisture, a multiple linear stepwise backwards regression was performed between the drawdown rates and antecedent moisture conditions. The independent variables included the H-hour antecedent mean water level (for H=3, 12, 24, 72) and the D-day antecedent rainfall depth (for D=3, 7, 15, 30), both assumed to represent the moisture conditions, as well as the height (to reduce the effects of a layered representation of the soil). We stopped the backwards regression process when the R² of the model was lower than 0.5 or when only two factors were left.

Finally, to smooth the model output (i.e. avoid the break of slope between layers) we weighted the hydraulic conductivity such that the exfiltration rate is continuous between layers, i.e.:

$$K_i(h_i) \times \left(h_i \frac{l_{rg}}{2} + A_{rg} \right) = K_{i-1}(h_i) \times \left(h_i \frac{l_{rg}}{2} + A_{rg} \right)$$

where $K_i(h)$ is the weighted hydraulic conductivity (m s⁻¹) function.

The weighting function was chosen as a linear function of height such that the total exfiltration over the layer is equal to that calculated with the non-weighted function, i.e.:

$$\int_{h_i}^{h_{i+1}} K_i(h) \times \left(h \frac{l_{rg}}{2} + A_{rg} \right) dh = \int_{h_i}^{h_{i+1}} K_i \times \left(h \frac{l_{rg}}{2} + A_{rg} \right) dh$$

Evapotranspiration from the raingarden. As the water level in the raingarden rarely drops below 0.5 m, ET from the raingarden was assumed to be equal to PET, set to the monthly average value given by the Bureau of Meteorology (2010). While this approach is likely to overestimate ET, it is justified by a sensitivity analysis showing the negligible contribution of ET to the total water budget (see Results). Only when the water level was lower than 0.5 m did we introduce a water stress function, decreasing the ET by a factor of four, based on the rate observed during the month of February 2009 when the hottest and driest conditions occurred. The ET was preferentially taken from the upper layers, i.e. the unsaturated zone in the raingarden, as the product of PET and a water stress function:

$$ET(\theta) = \begin{cases} 0 & \text{if } \theta < \theta_w \\ \frac{(\theta - \theta_w)}{\theta_{fc} - \theta_w} PET & \text{if } \theta_w < \theta \leq \theta_* \\ PET & \text{if } \theta > \theta_* \end{cases}$$

Where θ is the volumetric water content of the unsaturated upper layers of the raingarden; $\theta_w=0.1$ the wilting point; $\theta_*=0.22$ assumed to be the field capacity; and PET in mm/day (Daly et al. 2009). Therefore, only the difference between PET and ET from the unsaturated zone was extracted from the saturated zone.

The performance of the model was assessed via the Nash-Suttcliffe efficiency.

Surrounding soil moisture analysis

To characterize the impact of the raingarden on surrounding soil moisture, the drying rates over 1, 3 and 8 days (provided no rain occurred during these periods) were derived from the moisture sensors data. All dry spells of at least 24 hours were analysed and an ANOVA was performed to compare the drying rate of a given sensor to its equivalent sensor (at the same depth) at the other two distances from the raingarden. In addition, correlation analyses were performed between the drying rates and explanatory factors including the initial moisture content of the sensor, that of the sensors above and below (if any), the soil temperature and the meteorological parameters (incoming solar radiation, wind, air temperature and humidity). At this stage, a total of 11 spells were filtered over the first three months of data. It is noted that the data from the shallowest sensor (for each location) shows a rapid decrease in soil moisture, making the calculation of the drying rate straightforward. However, deeper sensors were sometimes affected by both the percolation from upper layers and the root uptake, which makes it more difficult to infer the drying rate. Events affected by such behaviour were discarded in the present analysis (although will be incorporated into future analyses, when a longer time-series is available). This percolation affected the drying rates calculated over 1 and 3 days; the 8-day average drying rate are less affected, with percolation negligible after the first 3-4 days. Unfortunately, few spells were long enough to calculate the 8-day average drying rate so the results presented at this stage focus only on the drying rates over 3 days (further data is currently being gathered and will be used to refine these calculations).

Finally, to assess the actual ET from the surrounding soils, potential ET was calculated from the FAO-56 Penman-Monteith equation for a grass reference crop (assumed to be similar to the lawn present on the site) with the data from the weather station. A water stress function was defined in a similar way to the above equation, with $\theta_w = 0.3$ and $\theta_* = 0.2$ derived from the literature (Li et al. 2001).

RESULTS AND DISCUSSIONS

Exfiltration rates

Exfiltration rates, derived from water level data, and the inferred hydraulic conductivities (K_i), varied strongly with depth (Table 1, Figure 2a). There was also large temporal variability in exfiltration rates, which was in part explained by antecedent conditions (Table 2). The best predictor varied between soil layers: water level was found to have a stronger effect on deeper layers (where the transition from high to low conductivity occurs); average water level was found to be a better predictor for K_{600} , K_{700} and K_{900} , while the antecedent precipitation over 30 days was found to better predict K_{800} . This is not surprising, given that rainfall will have most influence on the layers closest to the surface.

Two hypotheses are proposed to explain the data variability and the lack of consistent predictive factors. Firstly, the selected explanatory variables may not be representative as they are only a surrogate for soil moisture. Since the exfiltration rate is linked to the soil hydraulic conductivity, which is itself a function of soil moisture, a direct measurement of soil moisture is likely to provide much more reliable predictions. Such data will become available shortly from the recently-installed soil moisture probes. Secondly, we hypothesise that the exfiltration rate is not only dependent on intrinsic soil properties, but also a function of the soil moisture in the shallow (near-surface) layers and the presence of a low permeability layer below this. As the [600;700] mm layer has a very low hydraulic conductivity (see Figure 2a), it is likely that water from the shallow layers is prevented from seeping and instead flows towards the raingarden. This phenomenon only occurred during intense rain events and continued until the shallow layers reach field capacity. During this time, the measured exfiltration rate in the layers below is the difference between exfiltration from deep layers and infiltration (back into the raingarden) from the shallow layers above. This would explain the negative correlation between the measured infiltration rate in the upper layers (negative a_2 and a_1 values for $rate_{800}$ and $rate_{900}$, respectively: Table 2) as the increase in the hydraulic conductivity is offset by the backflow from the soil layers (Figure 2b).

Table 1. Drawdown rates from the water level data and inferred hydraulic conductivities

Depth range (mm)	[0;500]	[500;600]	[600;700]	[700;800]	[800;900]	[900;1000]
Sample size	16	83	69	22	11	4
Mean exfiltr. rate (mm/h)	0.20	0.67	3.29	62.5	97.2	90.3
St. dev (mm/h)	0.16	0.59	3.09	21.8	37.3	26.0
K_i (mm/h)	0.11	0.34	1.66	31.5	49.0	45.5

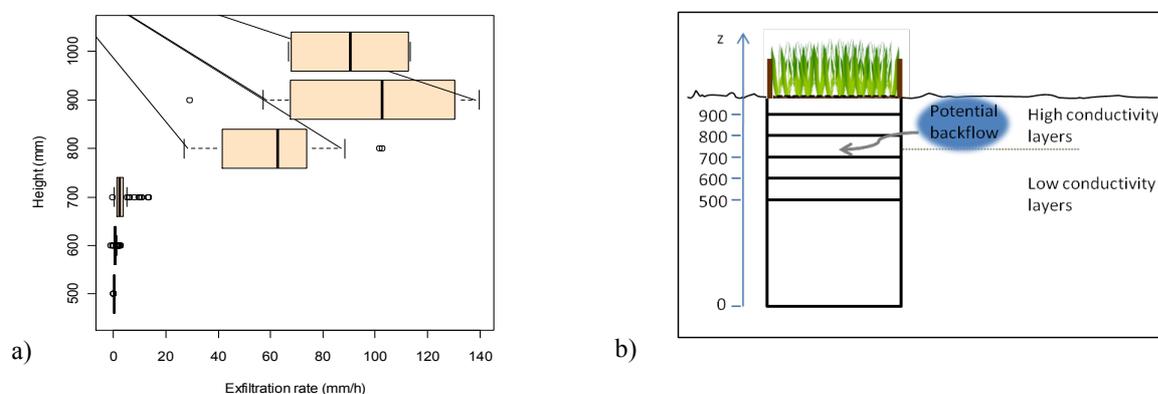


Figure 2. Hydraulic rate conductivity inferred from the exfiltration rates for 100 mm-thick layers (a) and schematic of the implications on a potential backflow from shallow layers (b)

Table 2. Summary of the results from the backwards stepwise regression analysis (factors included in the analysis were mean water level, antecedent level over 3, 12, 24 and 72 hours, and antecedent rain over 1, 7, 15 and 30 days); a_1 , a_2 and b are the regression coefficients

	Best predictors	R²	a₁	a₂	b
rate ₆₀₀	1. Height 2. Antecedent Level 3 h	0.74	-0.076	0.076	/
rate ₇₀₀	1. Height 2. Antecedent Level 72 h	0.58	0.0887	-0.02	-40.5
rate ₈₀₀	1. Antecedent Rain 30 d 2. Antecedent Level 72 h	0.53	0.512	-0.26	188
rate ₉₀₀	1. Antecedent Level 72h 2. Antecedent Rain 3d	0.73	-0.403	-1.02	362

Water balance

Over the 22 months of analysis, ET loss from the trench alone constituted < 3% of the influent volume, consistent with studies on biofiltration cells (Holman-Dodds et al. 2003). While some studies have suggested much greater losses (Hatt et al. 2009), they have not explicitly measured or modelled ET. Interestingly, the model predicted a total exfiltration volume larger than the inflow volume, sometimes by up to 50%. This finding corroborates the backflow theory explained above, where a significant volume of water from the shallow layers re-infiltrates the raingarden. However, uncertainties related to the exfiltration rates cannot be ignored and could also account for this difference between inflow and exfiltration. The monthly N-S efficiency averaged 0.5 during 2009, but negative values were found for half of the months in 2010 (i.e. during the validation period, when no exfiltration rate was measured). Further analyses are in progress to explain the difference in exfiltration rates during 2009 and 2010 results.

However, we note that the Nash-Suttcliffe efficiency measures the dynamic behaviour of the raingarden and should thus not be a criterion to reject completely the model. Specifically, an analysis of its uncertainties makes it possible to obtain reliable estimates of deep infiltration. Since the exfiltration rates of the layers below 600 mm are very low, the confidence interval for the amount of water exfiltrated in deep layers is relatively small (the 95% confidence interval for the <600 mm-exfiltration rates is [0; 1.85] mm/h). Therefore, we can observe that 10 % of the treated water will directly infiltrate to deep layers, with a maximum range of [0; 30%]. This means that the majority of the filtered flow is exfiltrated into shallow layers (less than 0.4 m-deep), a depth which corresponds to the root zone depth observed during field work (in accordance with typical values for grass, Fox et al. 1953). As a result, this water is available for ET and only the excess water will slowly percolate to deeper layers.

Statistical analyses of dry spells and total water budget

Drying rates. The drying rates measured from the three sets of sensors are reported in Table 4. As expected, the deepest sensors from Set 1 are always at saturation and show no significant variation over time. Also, the slow drying rate from the 0.85 m-deep reference sensor (Set 3)

Table 2. Average water balance of the raingarden; ET is from the raingarden only; the exfiltration volume does not account for the potential backflow from surrounding soils

	Rain (mm)	Inflow (m ³)	ET (m ³)	Exfiltration (m ³)	
				<600 mm	>600 mm
Mean	95.0	30.6	0.81	3.14	26.6
St.Dev	49.6	16.9	0.4	0.9	16.5
%	-	100	2.7	10.3	87.0

Table 3. Drying rates (mm/h) over three days at the five depths for each set of sensors (Sets 1 and 2 are 0.5 m and 3.5 m from the raingarden, respectively; Set 3 is the reference location)

Moisture sensor set (distance from raingarden)	Depth (m)				
	0.1	0.2	0.32	0.6	0.85
Set 1 (0.5 m)	16	3.2	0.4	<0.2	<0.2
Set 2 (3.0 m)	13	6.1	1.3	<0.2	1.0
Set 3 (9.0 m)	6.2	4.7	4.3	1.2	1.7

is consistent with the range of hydraulic conductivities expected at that depth, which provides confidence in the measured values. Interestingly, the drying rates at shallow depth (0.1 m) show significantly different values (ANOVA $p < 0.005$), ranging from 6 mm/h for the reference set to 16 mm/h for the sensor from Set 1. Given the very low conductivity at 0.4 m depth, the high drying rate measured next to the trench may be explained by a lateral flow back into the trench, which corroborates the backflow phenomenon discussed above.

Finally, we note that the limited period of data for the soil moisture precludes any conclusion on the behavior of Set 2 (i.e. if it is more similar to Set 1 or to Set 3). While the results show significant differences between the drying rates, it is too early to deduce the lateral influence of the raingarden on surrounding soils. These results will determine the influence area of the raingarden which may present increased ET losses.

ET from surrounding soil. The calculation of PET over the study period confirmed the low values expected from the wet weather, since it average 2.5 mm/day (about twenty times lower than the drying rates). Furthermore, sensors indicated that the average water content over the root zone did not drop below θ_* such that the plants did not experience water stress. Hence, actual ET was equal to PET for all locations, with no noticeable influence from the raingarden. These results are substantiated by the correlation analyses, showing that drying rates were not significantly influenced by meteorological variables (thus ET was not a key driver of the observed drying rate).

Therefore, the ET loss from the soils surrounding the raingarden was not different from that of the reference point (already at its maximal PET) and as a consequence, all exfiltrated water effectively recharged groundwater. To put these results in perspective, it is noted that they rely on: i) the specific vegetation (only comprised of grass in the surrounding area so that no tree could have withdrawn larger amounts of water); ii) the climatic conditions, which were unusually wet for over the first two months of data, meaning that the vegetation did not suffer water stress during this initial period of soil moisture monitoring.

CONCLUSIONS AND FUTURE RESEARCH

Water balance of the Rangeview raingarden. A methodology was proposed that allows the calculation of the total water budget from an infiltration system. In the particular case of heavy clay soils, it showed that the traditional approach to calculate a system's water balance (focusing on the ET from the raingarden only) is likely to underestimate the total ET. We have shown that more than 70% of the exfiltrated water is released into the shallow soil layers, where further ET is likely. As percolation occurs at a very slow rate (less than 1 mm/h), the soil water is available for plant uptake. However, the limited period of soil moisture data available for this study does not indicate such an enhancement of ET. As the plants did not experience a water stress, ET near the raingarden was equal to actual evapotranspiration similar to that in the reference area 9 m from the raingarden. In any case,

the ET was negligible compared to seepage. This implies that during the studied period, virtually all the exfiltrated water has recharged groundwater. Moreover, given the unusually wet weather, the lateral extent reached by the exfiltrated water in the shallow layers cannot be ascertained from the first months of data.

Contribution and further research. In addition to the analysis of further months of data, several improvements to the proposed model are in progress. Firstly, the raingarden exfiltration model will be tested with a new statistical approach (information theoretic approach) to identifying and assessing the optimal models for predicting exfiltration rates. In addition, the model will be developed using the directly-measured soil moisture and exfiltration rates. This is expected to improve the efficiency of the model which is currently based on surrogate measures of soil moisture (antecedent precipitation and water level in the raingarden). In addition, a soil water model is being developed to directly calculate ET from the soil moisture profile in the surroundings of the raingarden. This model will be validated by measurements by ET flux chambers scheduled for late April.

The final results of this study will have significant implications for the design of infiltration systems. Specifically, the assessment of their potential contribution to ET and groundwater recharge will be improved and will inform catchment scale stormwater management strategies which aim to restore pre-development hydrology.

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