Quantifying Evapotranspiration from Vegetated Sustainable Drainage Systems using the 3T Method

Quantification de l'évapotranspiration des systèmes de drainage durable végétalisés à l'aide de la méthode 3T

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RÉSUMÉ

Les taux d'évapotranspiration (ET) des systèmes de drainage durable (SuDS) diffèrent significativement des taux d'ET de référence en raison des différences de types de végétation, de disponibilité en eau et du contexte urbain. Une technique permettant de quantifier les taux d'ET in situ serait d'une grande utilité pour les professionnels de la conception et de la modélisation du drainage urbain. Dans cet article, nous présentons et discutons les résultats d'un exercice de suivi continu sur le terrain visant à évaluer si la méthode 3T peut fournir des données d'ET robustes dans ce contexte. La méthode 3T repose sur la mesure de trois températures : les températures de surface d'une feuille en transpiration et d'une feuille artificielle, ainsi que la température de l'air. Des estimations/mesures du rayonnement net à la surface des feuilles (végétée et artificielle) sont également nécessaires. Les résultats d'une étude de suivi continu montrent une forte corrélation entre l'ET mesurée par la méthode 3T et les pertes d'ET déterminées directement à l'aide d'un lysimètre à pesée. Cependant, il convient de veiller à ce que les mesures soient effectuées dans des conditions atmosphériques valides, ce qui peut limiter les périodes de mise en œuvre.

ABSTRACT

Evapotranspiration (ET) rates from Sustainable Drainage Systems (SuDS) differ significantly from reference ET rates due to differences in vegetation types, water availability and the urban setting. A technique capable of quantifying ET rates *in situ* would be of considerable value to urban drainage design and modelling professionals. In this paper we present and discuss findings from a continuous field monitoring exercise aimed at assessing whether the 3T method can deliver robust ET data in this context. The 3T method is based on the measurement of three temperatures: the surface temperatures of a transpiring leaf and an imitation leaf, alongside the air temperature. Estimates/measurements of the net radiation at both the vegetated and imitation leaf surfaces are also required. Results from a continuous monitoring study show a strong correlation between 3T-ET and ET losses determined directly using a weighing lysimeter. However, care must be taken to ensure that the measurements are made under valid atmospheric conditions, which may restrict time windows available for its deployment.

KEYWORDS

Evapotranspiration (ET), Green Infrastructure (GI), Remote Sensing (RS), Sustainable Drainage Systems (SuDS), Three Temperatures (3T),

1 INTRODUCTION

Evapotranspiration (ET) rates from Sustainable Drainage Systems (SuDS) differ significantly from reference ET rates due to differences in vegetation types, water availability and the urban setting. A technique capable of quantifying ET rates *in situ* would be of considerable value to urban drainage design and modelling professionals.

The 3T method was originally presented by Qiu *et al.* (1996), and has already met with some degree of success in the context of urban SuDS (Zhang *et al.,* 2020; Qiu *et al.*, 2017; 2021). The method is derived from the surface energy balance; its full derivations and parameter estimation techniques can be found in Qiu *at al.* (1996) or Wickham *et al.* (2025). The 3T method (Figure 1) is based on the measurement of three temperatures: the surface temperatures of a transpiring leaf and an imitation leaf, alongside the air temperature. Estimates/measurements of the net radiation at both the vegetated and imitation leaf surfaces are also required. The last term in the equation presented in Figure 1 is referred to as the 'temperature fraction'.

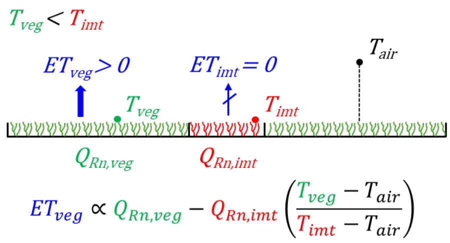

Figure 1 – A conceptual diagram of the three temperatures (3T) method

Figure 2 – Imitation surfaces: left – Wickham et al. (2025); right – modified surface. The modular cells sit on aluminium trays connected to the load cells.

Wickham *et al.* (2025) presented a preliminary evaluation of the 3T method using continuous measurements made in a semi-controlled environment. In this exercise comparisons were made to Reference ET (ET_o), with the 3T-ET estimates consistently over-estimating ET_o. However, direct measurement of actual ET were not available to confirm whether actual ET also exceeded ET_o. The present work builds upon Wickham *et al.* (2025) in three key aspects: (i) the reference surface has been modified to better reflect the thermal behaviour of the vegetation; (ii) the measurements were made during summer conditions when absolute ET rates were expected to be higher, and issues relating to building shadowing should be less critical; and (iii) direct measurements of ET were made in parallel with the 3T measurements using a load cell.

2 MATERIALS AND METHODS

The experiment was set up for a homogeneous surface of standard amenity grass turf mat. Two test beds were established on a roof space on the University of Sheffield (UK) campus. The first test bed was monitored with a net radiometer, a shielded air temperature and relative humidity sensor and a three-cup wind anemometer. The second test bed comprised 15 modular cells (0.25 m x 0.25 m) arranged in a [3, 5] grid. Fourteen of the cells reproduced the grass surface, while the final cell – located at position [2, 2] – incorporated the imitation surface. The imitation surface comprised plastic artificial grass with plastic grass stalks woven into it to match the height and roughness characteristics of the amenity grass (Figure 2).

Each of the modular cells was positioned on a calibrated load cell with a safe loading capacity of 10 kg. Surface temperatures were measured for the imitation surface and the only vegetated cell completely surrounded by other vegetated cells (i.e. position [2, 4]) using infrared radiometers. All the sensors were connected to one of two synchronised CR1000X data loggers. Data was collected at one-minute intervals between 06/07/24 and 10/10/24, a continuous period of 97 days. The grass was maintained at a height of approximately 0.12 m, watered twice weekly and fertilised to meet the requirements of a standard reference crop (Allen *et al.*, 1998).

The load cell data was smoothed prior to extracting the hourly values and converting to ET rates in mm/hr. The one-minute microclimate data was averaged over each hour to generate an hourly estimate of 3T-ET. A full description of the method can be found in Wickham *et al*. (2025). Data associated with periods of watering and rainfall were excluded from the analysis.

Reference ET values (ET_o) were derived using the FAO-56 Penman-Monteith hourly method (Allen *et al.*, 1998).

3 RESULTS

Figure 3a) shows the temperature measurements associated with the ten-day period 1-10 August 2024, clearly demonstrating the expected diurnal cycles. Air temperatures exceed the surface temperatures at night, with the reverse occurring during daytime hours. However, it may be seen that there are occasions early in the afternoon when T_{air} exceeds T_{veg}, as a result of the urban heat island in this densely built-up setting.

Figure 3b compares the 3T-ET estimates with the associated measured (actual) ET (load cell) and ET_o data. The unfiltered 3T-ET data (dotted blue line) shows many instances when unreasonable 3T-ET values were produced. These reflect atmospheric conditions for which the approach is invalid, for example when $T_{veg} > T_{imt}$. Two filters were therefore applied to the 3T-ET results:

- Filter 1 only includes data for which $T_{imt} > T_{veg} > T_{air}$.
- Filter 2 includes data for which $T_{imt} > T_{veg} > T_{air}$ or $T_{imt} > T_{air} > T_{veg}$ and also limits the temperature fraction to values >-1. This filter is comparable to that applied in Wickham *et al.* (2025).

Figure 3b) presents the 'Filter 1' (blue crosses) and 'Filter 2' data (blue circles). While the number of 'valid' measurements associated with Filter 1 is quite small (approximately 7% of the complete continuous data set), the correlation between these data points and the measured (load cell) ET rates is excellent, whereas the Filter 2 data includes many values that overestimate ET compared with the measured data.

Note that it also clear from this plot that actual ET in this context was enhanced with respect to ET_o.

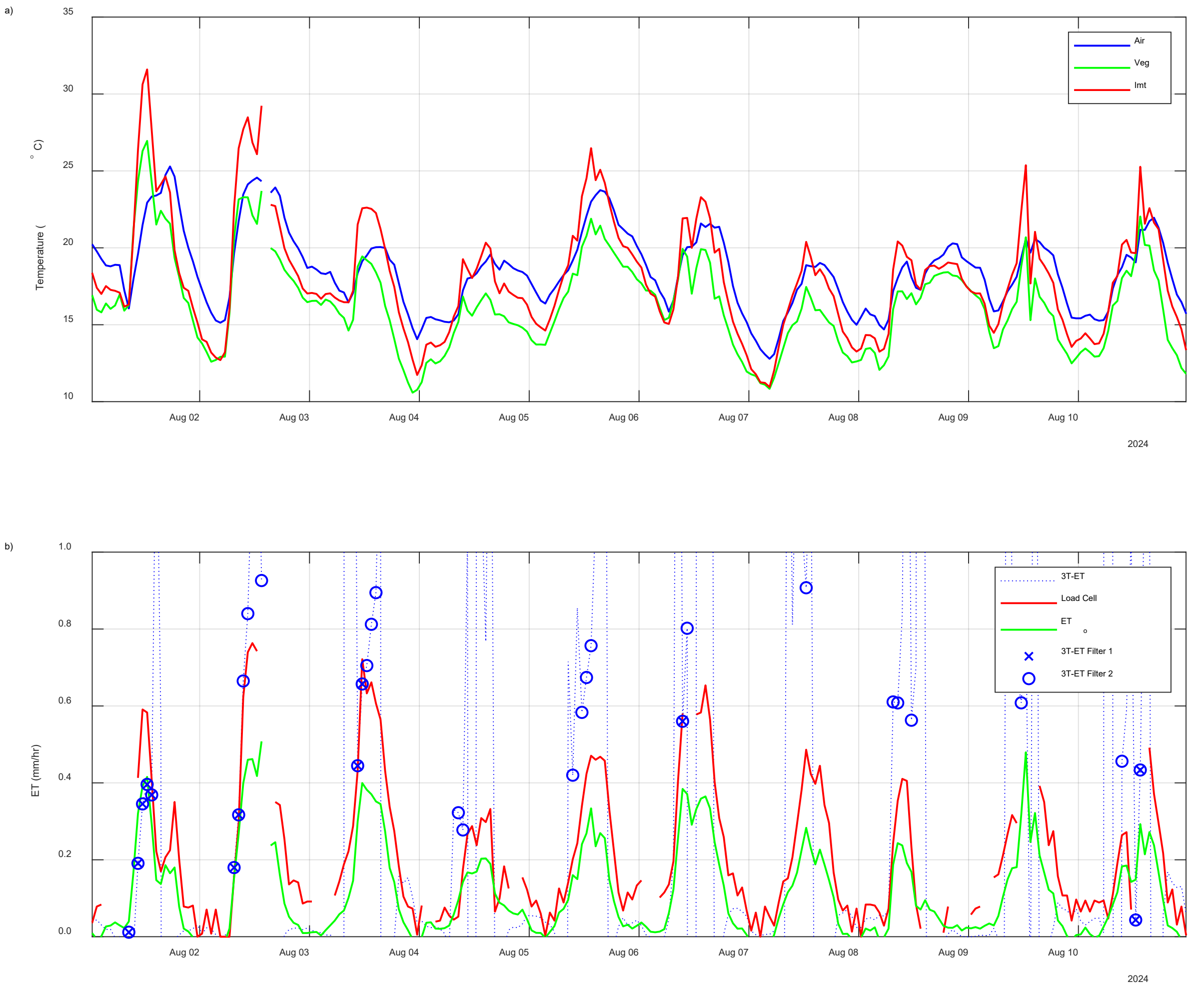

Figure 3 – Time-series of a) Temperature and b) ET_o, Measured ET (load cells) and ET estimated using the 3T method for 10 days in August 2024

Figure 4 compares all valid data points over the full three-month monitoring period. The Filter 1 data is a subset of the Filter 2 data, which includes more than twice as many data points as Filter 1. However, Figure 4 clearly shows that the Filter 1 data matches the line of equality (dotted black line) very well. On the other hand, while Filter 2 includes more observations, the vast majority of the additional points lead to an over-estimate of actual (i.e. measured) ET. Simple linear regression for the Filter 1 (i.e. T_{imt}> T_{veg}> T_{air}) data results in a slope that is close to unity and an R^2 that exceeds 0.82. The RMSE is less than 0.1 mm/hr and PBIAS is close to zero, all of which indicate a good match between the measured and estimated values. For Filter 2 (i.e. T_{imt}> T_{veg} , T_{imt}> T_{air} and TF > -1), on the other hand, the slope deviates notably from unity, the R^2 is less than 0.7, RMSE exceeds 0.1 mm/hr and BPIAS (+25%) further confirms the significant positive bias in the data when the -1 < TF < 0 data is included.

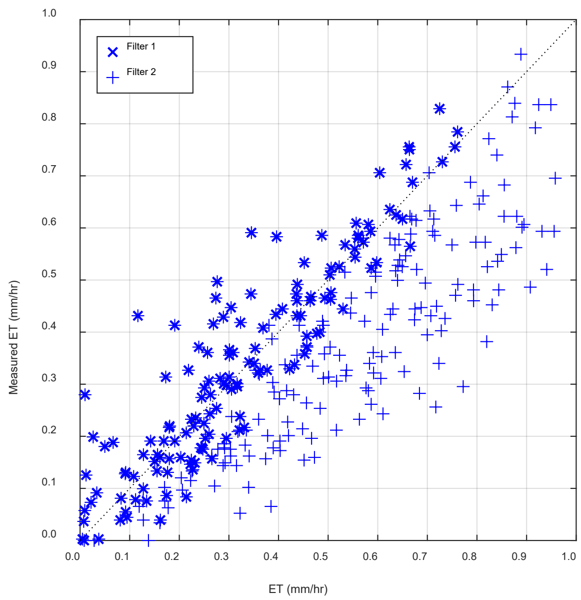

Figure 4 – Comparison of 3T-ET estimates against measured (load cell) ET

4 CONCLUSIONS

The 3T method potentially provides a relatively straightforward and robust method for quantifying ET from non-standard vegetation (i.e. SuDS and Green Infrastructure) in urban settings. However, the method only produces reliable data when atmospheric conditions meet the criteria $T_{imt} > T_{veg} > T_{air}$. This may restrict time windows available for its practical deployment. Additional work is required to understand whether further refinements to the method might overcome this limitation. The microclimatic data highlights the effect of the urban heat island in this densely built-up setting.

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