# Estimation of Evapotranspiration from Sustainable Drainage Systems using the Bowen Ratio Method

## Estimation de l'évapotranspiration des systèmes de drainage durable à l'aide de la méthode du rapport de Bowen

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## RÉSUMÉ

L'évapotranspiration (ET) de la végétation est un élément clé des bilans hydriques et énergétiques urbains. La perte d'humidité entre les épisodes de pluie crée une capacité de stockage des eaux pluviales, réduisant ainsi le risque d'inondation et les débordements d'égouts unitaires dans les cours d'eau urbains. Cependant, les incertitudes entourant les estimations d'ET des infrastructures vertes constituent un frein à leur déploiement à plus grande échelle et à la prédiction de leurs performances. Cette étude examine la capacité de la méthode du ratio de Bowen à estimer les taux d'ET d'un système de drainage urbain durable (SUDS) végétalisé à l'échelle pilote, en milieu urbain. Le ruissellement, le rayonnement net, le flux de chaleur du sol, la vitesse du vent, la température de l'air et l'humidité relative ont été mesurés en continu pendant six mois, à intervalles d'une minute. Les mesures de température et d'humidité à trois hauteurs ont permis de calculer l'ET, à la fois pour une parcelle témoin non végétalisée et pour des parcelles végétalisées, en utilisant la méthode du ratio de Bowen. Ces estimations ont été comparées aux valeurs d'ET calculées à partir de l'équation standard FAO-56 de Penman-Monteith. Les résultats montrent que les estimations d'ET obtenues par les deux méthodes sont cohérentes pour les parcelles végétalisées et non végétalisées. La méthode du ratio de Bowen a permis d'obtenir des estimations d'évapotranspiration (ET) raisonnables pour le banc d'essai végétalisé, ce qui indique son potentiel d'application à plus grande échelle, notamment lorsqu'elle est intégrée à des données de télédétection pour une évaluation de l'ET à plus grande échelle. Les travaux futurs examineront la performance de cette méthode sur un plus large éventail d'infrastructures vertes.

## ABSTRACT

Evapotranspiration (ET) from vegetation is a key component of urban water and energy budgets. The moisture loss occurring between storm events creates storage capacity for rainfall, thereby reducing flood risk and mitigating combined sewer overflow events in urban watercourses. However, uncertainties surrounding ET estimations from green infrastructure remain a barrier to broader implementation and performance prediction. This study investigates the capability of the Bowen Ratio method for estimating ET rates from a testbed-scale vegetated Sustainable Drainage System (SuDS) device in an urban environment. Rainfall-runoff, net radiation, soil heat flux, wind speed, air temperature, and relative humidity were continuously monitored over a six-month period at 1-minute intervals. Temperature and humidity measurements at three heights were used to calculate ET for both an unvegetated control test bed and vegetated test beds using the Bowen Ratio approach. These estimates were compared with ET values calculated from the standard FAO-56 Penman-Monteith equation. The results show that ET estimates generated by the two methods were consistent for both the vegetated and unvegetated test beds. The Bowen Ratio method produced reasonable ET estimates for the vegetated test bed, indicating its potential suitability for wider application, particularly when integrated with remote sensing data for larger-scale ET assessment. Future work will examine the method’s performance across a broader range of green infrastructure types.

## KEYWORDS

Air Temperature, Bowen Ratio, Evapotranspiration, Sustainable Drainage Systems, Relative Humidity.

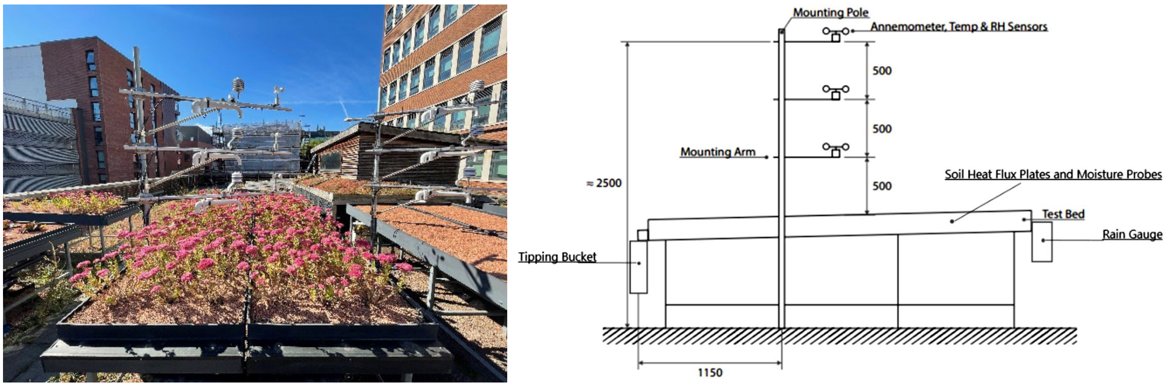
## 1 INTRODUCTION

The ability to estimate water losses from vegetated Sustainable Drainage System (SuDS) devices through evapotranspiration (ET) is critical for the effective design and implementation of green infrastructure (Wadzuk et al., 2013). Direct methods for measuring ET include monitoring changes in soil moisture content within the growing media or using weighing lysimeters. However, the vertical and spatial variation in moisture content within growing media introduces uncertainty into ET estimates derived from point-based soil moisture measurements (Poë et al., 2015). Weighing lysimeters, while considered the most accurate direct method, are impractical for use at larger SuDS scales. As a result, non-intrusive ET estimation methods that rely on meteorological measurements are commonly used. These approaches involve monitoring variables such as net radiation, soil heat flux, wind speed, air temperature, and relative humidity, and then estimating ET from the resulting surface energy fluxes. Widely used methods include the Bowen Ratio energy balance method and the standard Penman-Monteith equation. Although the Bowen Ratio method has been extensively validated for large-scale agricultural fields (Pieri and Fuchs, 1989), its reliability for small-scale, vegetated SuDS installations in complex urban environments has not yet been assessed. This study, therefore, aims to evaluate the suitability of the Bowen Ratio method for estimating ET from both unvegetated and vegetated SuDS test beds, using high-resolution meteorological data collected in an urban setting in Sheffield, UK.

## 2 METHODS

### 2.1 Test Beds and Data Collection

Four SuDS test beds of 2 m (width) × 3 m (length) were installed on the rooftop of the Hadfield Building at the University of Sheffield (Fig.1). One test bed was left unvegetated, while the remaining three were planted with vegetation. Each test bed comprised, from bottom to top, a plastic base layer, a drainage layer, a filter layer, an 80 mm substrate layer, and a vegetated layer. Instruments were installed on each test bed to monitor hydrological and meteorological variables. A rainfall gauge and a runoff measurement device were positioned at the side and bottom of each bed. Two soil heat flux plates were embedded at mid-depth within the substrate, placed at two locations in each bed. Three wind speed sensors and combined air temperature and relative humidity sensors were mounted vertically above each test bed surface at nominal heights of 0.5 m, 1.0 m, and 1.5 m (Fig.1). A net radiometer was installed adjacent to the unvegetated test bed. All sensors were logged at a 1-minute temporal resolution from 1 March 2021 to 31 August 2021.




(a) (b)

Fig. 1. The Test Beds (a) and Instrumentation Set-up (b).

### 2.2 Bowen Ratio and Penman-Monteith Methods

The Bowen Ratio method estimates sensible and latent heat fluxes, and is based on the assumption that the eddy diffusivities for heat and water vapour are equal, such that the same turbulent eddies transport both quantities. This implies that the surface sources of heat and vapour are uniformly distributed, and therefore the ratio between sensible and latent heat flux densities remains constant between any two measurement heights. A key advantage of this method is that it requires only air temperature and vapour pressure measurements at two heights above the vegetation surface. Using these measurements, along with net radiation and soil heat flux, evapotranspiration can then be calculated through the surface energy balance equation. In this study, the measured relative humidity was converted to vapour pressure using an empirical equation. As measurements were available at three heights, the temperature-vapour pressure gradient was determined by fitting a linear curve to the three data points. The Penman-Monteith equation is widely recognised as the standard method for calculating reference evapotranspiration from vegetated surfaces. In this study, the FAO-56 formulation was used to evaluate the performance of the Bowen Ratio method in estimating evapotranspiration from both the unvegetated and sedum-vegetated test beds.

# 3 RESULTS

## 3.1 Unvegetated Test Bed

Figure 2(a) presents the measured vertical profiles (over height Z) of wind speed, air temperature, and relative humidity above the unvegetated test bed. The data were normalised by their mean values, and each profile represents the monthly averaged profile, with error bars showing the standard deviation. The wind speed profile exhibits the greatest variability, and its shape suggests a tendency toward slightly unstable atmospheric conditions. In contrast, the temperature and humidity profiles display more consistent logarithmic behaviour with comparatively small variation. The temperature profile shows slightly lower temperatures near the surface on average, which may indicate that the soil is absorbing energy, resulting in downward sensible and latent heat fluxes. Figure 2(b) shows measured net radiation ($R_n$) and soil heat flux ($Q_G$), together with the estimated sensible ($Q_H$) and latent ($Q_E$) heat fluxes using the Bowen Ratio method for a selected day. As expected, soil heat flux is negligible relative to the other energy components. Net radiation follows the typical diurnal cycle, with positive values during daytime and negative values at night. Figure 2(c) compares hourly evapotranspiration (ET) rates estimated using the Bowen Ratio method with hourly ET rates derived from the FAO-56 Penman-Monteith equation. The Bowen Ratio ET is consistent with the FAO-56 estimates, although it tends to underestimate the ET, especially after midday. Figure 2(d) shows the daily mean ET values estimated by both methods over an entire month (August 2021). The coefficient of determination ($R^2$) indicates the overall performance of the Bowen Ratio method (compared to the FAO-56 Penman-Monteith method), and the regression line illustrates the systematic shift between the Bowen Ratio and FAO-56 estimates. The Bowen Ratio method tends to underestimate ET at lower ET rates and overestimate ET at higher ET rates, with the largest discrepancies reaching up to approximately 50%.

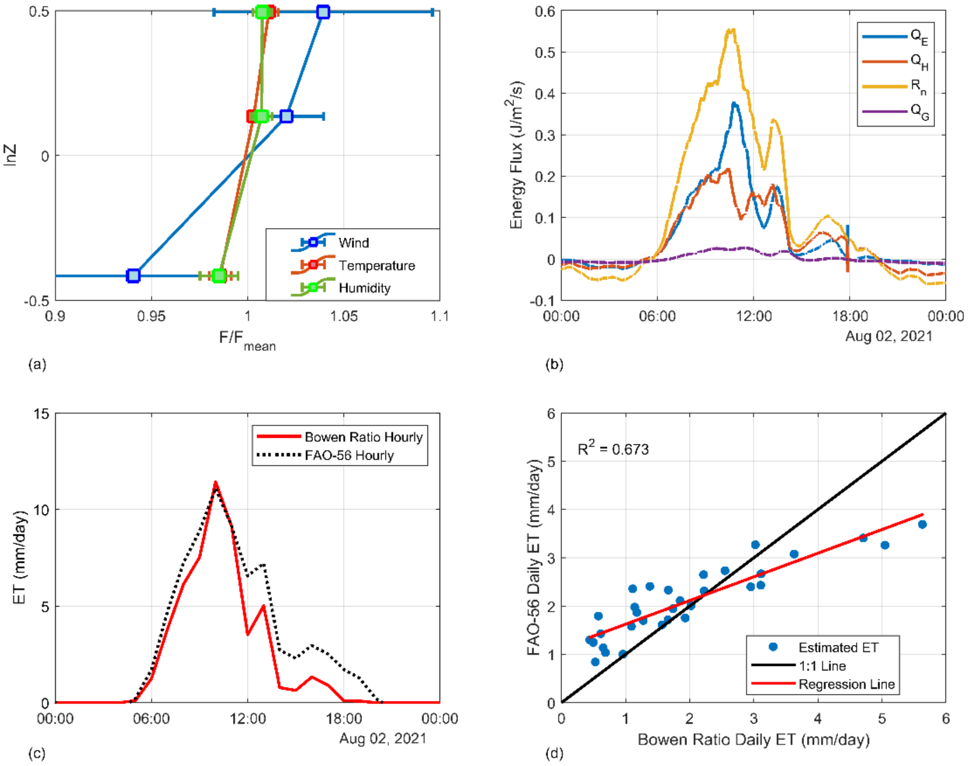



Fig. 2. Measured Vertical Profiles, Measured and Estimated Energy Fluxes, and modelled Evapotranspiration for Unvegetated Test Bed.

## 3.2 Sedum Vegetated Test Bed

Figure 3 presents the results for the sedum-vegetated test bed. All three measured profiles exhibit a clear logarithmic shape (Fig. 3(a)). The temperature and humidity profiles display negative gradients, with higher values near the surface, indicating upward sensible and latent heat fluxes, the opposite pattern to that observed for the unvegetated test bed. The estimated sensible and latent heat fluxes also show greater daytime variability and more fluctuations compared to the unvegetated bed (Fig. 3(b)). The comparison between hourly ET rates estimated using the Bowen Ratio method and those obtained from the FAO-56 Penman-Monteith equation (Fig. 3(c)) shows improved consistency for this vegetated test bed. Likewise, the daily mean ET values calculated over the entire month exhibit better agreement between the two methods (Fig. 3(d)) than was observed for the unvegetated test bed. The regression line in Fig. 3(d) indicates that the Bowen Ratio method tends to overestimate ET rates, with the largest discrepancies reaching approximately 20% above the FAO-56 estimate. Because no crop coefficient was applied, differences between the two methods may be caused by the different characteristics of soil or sedum vegetation compared with the FAO-56 reference vegetation.

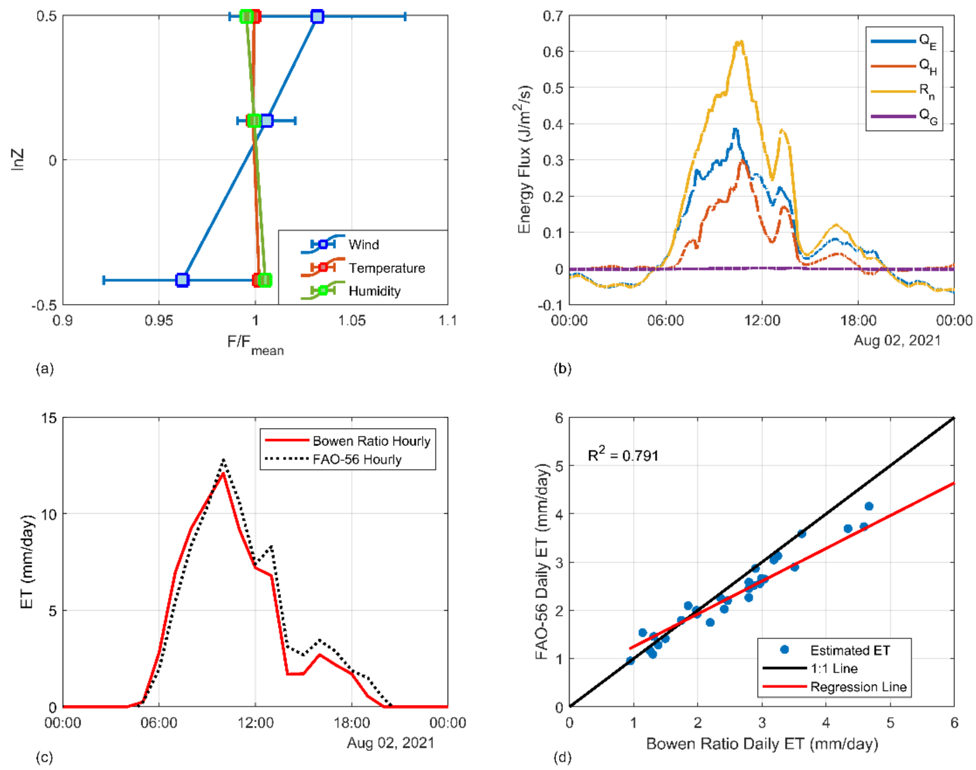



Fig. 3. Measured Vertical Profiles, Measured and Estimated Energy Fluxes, and modelled Evapotranspiration for Sedum Vegetated Test Bed.

# 4 CONCLUSIONS

Net radiation, soil heat flux, wind speed, air temperature, and relative humidity were monitored from four small-scale SuDS test beds situated in an urban environment. The temperature and humidity profiles indicated slightly higher values near the surface of the vegetated beds compared with the unvegetated bed. The collected data were used in both the Bowen Ratio method and the FAO-56 Penman-Monteith equation to estimate time-series ET rates. The Bowen Ratio method provided a reasonable estimation of ET and performed better for the vegetated test bed, indicating its potential suitability for broader application, especially when combined with remote sensing data for larger-scale ET estimation.

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