



 <https://doi.org/10.71573/9mdyym66>

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Impacts of climatological variability on Evapotranspiration: A Sensitivity Analysis for Urban Drainage Applications

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Abstract

Understanding the sensitivity of reference evapotranspiration (ET_o) to meteorological variables is critical for improving urban water management and climate adaptation strategies. This study analyses the one-way and two-way sensitivity of ET_o to maximum temperature (T_{max}), wind speed (u_2), net solar radiation (R_n), and maximum relative humidity (RH_{max}) using the FAO-56 Penman-Monteith equation for multiple meteorological stations in Paris area. One-way sensitivity analysis revealed that T_{max} and R_n have the strongest influence on ET_o in summer, while wind speed and RH_{max} show secondary but notable effects, particularly in winter and transitional seasons. A two-way sensitivity analysis was conducted for T_{max} and RH_{max} , considering their joint influence on vapor pressure deficit (VPD). The results indicate a nonlinear relationship, where higher T_{max} and lower RH_{max} significantly increase VPD, amplifying ET_o , while increasing RH_{max} dampens this effect. Seasonal variations highlight stronger ET_o sensitivity in summer and reduced impact of R_n in winter due to high humidity levels. Windspeed has its major role in shaping evapotranspiration in winter and in dense urban settings. These findings emphasize the need for climate-adaptive urban drainage models, integrating ET_o variability to enhance stormwater retention, flood resilience, and green infrastructure efficiency under changing climate conditions. Future research should refine ET_o modelling for urban microclimates, ensuring accurate water balance predictions in cities.

Highlights

- Climate-driven shifts in temperature and humidity impact ET_o
- Temperature and solar radiation dominate ET_o variability in summer
- Integrating ET_o variability in model improves the stormwater management and resilience.

Introduction

Urban drainage systems are increasingly challenged by the impacts of climate change, including shifts in precipitation patterns, rising temperatures, and intensified extreme weather events. Among the many hydrological components influencing urban water balance, accurate estimation of reference evapotranspiration (ET_o) is critical for optimizing stormwater management, green infrastructure design, and hydrological modelling. However, ET_o is highly sensitive to meteorological variables such as temperature, solar radiation, wind speed, and relative humidity, all of which are shifting in urban area due to the impact of the built environment and of the climate change. Expected rise in temperature in future climate with less mean annual precipitation can give an overall rise to vapor pressure deficit thus increasing atmospheric evaporative demand. (Noto et al., 2023a). Along with this, uncertainty and insufficiency of evapotranspiration estimation models, uncertainty in metrological data sets and

applicability of urban drainage models in different urban environments can lead to overestimations or underestimations of stormwater runoff, affecting the design and efficiency of Sustainable Urban Drainage Systems (SUDS) (Sytsma et al., 2022). Similarly, meteorological data obtained from urban meteorological stations is mainly observed in wide open spaces where temperature is usually lower, solar radiation is more direct and windspeed is higher due to almost no resistance in surrounding. Given the increasing variability in climate drivers, quantifying the response of ET_o to both the spatial variability of climate drivers in urban areas and the temporal changes expected due to climate change is essential for improving the resilience and predictive accuracy of urban hydrological models. This study conducts a sensitivity analysis of ET_o using the FAO-56 Penman-Monteith equation, assessing the relative influence of key climatic drivers in urban environment (Emeka et al. 2021). By systematically varying these parameters and evaluating their respective impacts on ET_o , this paper aims to identify the dominant climate drivers controlling urban evapotranspiration and their implications for stormwater management, green infrastructure planning, and urban flood mitigation strategies. By bridging the gap between hydroclimatic sensitivity analysis and urban drainage modelling, this research seeks to integrate climate-adaptive ET_o predictions into urban water management strategies. Additionally, this research also tries to understand the feasibility of using Penman model along with data available through meteorological station in urban drainage modelling.

Methodology

Baseline Reference Evapotranspiration (ET_o)

The sensitivity analysis of ET_o using the FAO-56 Penman-Monteith equation examined the effects of maximum temperature (T_{max}), wind speed (u_2), net radiation (Rn), and maximum relative humidity (RH_{max}) across multiple meteorological stations covering urban and suburban environments (Allen et al., 1998).

One-Way Sensitivity Analysis

One-way sensitivity analysis involved varying each independent variable (T_{max} , u_2 , Rn, RH_{max}) individually by applying percentage perturbations from -25% to +25% in steps of 5%, building 10 scenarios in the observed value, while keeping all other variables constant. For each perturbed scenario, ET_o was recalculated, and the sensitivity coefficient (SC_x) was derived for the perturbed variable X using the following equation:

$$SC_x = \frac{\frac{ET_{o_x} - ET_{o_{Base}}}{ET_{o_{Base}}}}{\frac{X_P - X_{base}}{X_{Base}}} = \frac{\Delta ET_o / ET_{o_{Base}}}{\Delta X / X_{Base}}$$

Here, $ET_{o_{Base}}$ represents the baseline ET_o computed using observed data, while ET_{o_x} is the recalculated ET_o using the perturbed value X_P of the selected variables. A sensitivity coefficient (SC) was calculated for each variable by dividing the relative change in ET_o by the relative change in the variable. The mean daily and annual sensitivity coefficient across all scenarios was computed providing a scalar value representing the sensitivity of ET_o to respective variable. This approach has been widely used as a simple and reliable method for sensitivity analysis (Irmak et al. 2006; Emeka et al. 2021).

Two-Way Sensitivity Analysis

In the two-way sensitivity analysis, the combined effect of varying maximum temperature (T_{max}) and maximum relative humidity (RH_{max}) on reference evapotranspiration (ET_o) was investigated. Perturbations ranging from -25% to +25% were applied simultaneously to T_{max} and RH_{max} , resulting in a grid of perturbation combinations (T_{max-PP} , RH_{max-PP}). For each combination of T_{max-PP} and RH_{max-PP} , corresponding changes in vapor pressure deficit (VPD) were computed, as VPD is a dependent variable influenced by both T_{max} and RH_{max} . Using the perturbed T_{max-PP} , RH_{max-PP} , and the corresponding perturbed VPD values, ET_o was recalculated for each perturbation combination employing the Penman-Monteith equation.

Case study

This analysis is conducted in the metropolitan area of Paris over a one-year period (20th June 2022 – 19th June 2023). The study included nine stations, covering different urban and suburban environments, ensuring diverse microclimatic conditions. Out of 9 metrological stations, 2 stations (Sensecity and Breuil) are associated to SUDS experimental facilities surrounded by buildings, 3 stations (Beauvais, Orly and Roissy) are on airports grounds, 2 stations (Montsouris and Longchamp) are from Paris city centre and 2 stations (Melun and Trappes) are in the suburban areas of Paris.

Results and discussion

Although, local weather conditions, latitude and altitude of the area, urban setting and time of year alters the course of sensitivity the relation of investigated input variables with ET_o remains similar as observed in these results. T_{max} , R_n and u_2 positively affect the ET_o while RH_{max} negatively impacts the ET_o , whereas vapour pressure deficit has a nonlinear behaviour (Table 1).

The comparison of ET_o across urban environments highlights the role of microclimatic variations, particularly wind speed differences in dense urban and suburban areas (Figure 1a). Using suburban meteorological data for SUDS modeling in dense urban areas introduces uncertainties due to microclimate differences, amplified by climate change.

Table 1. Average annual Sensitivity coefficient of selected independent variables across all stations

Region	Sencecity	Breuil	Orly	Beauvais	Roissy	Montsouris	Longchamp	Melun	Trappes
SC_T	0.429	0.357	0.522	0.459	0.520	0.488	0.503	0.381	0.451
SC_RH _{max}	-0.546	-0.407	-0.454	-0.570	-0.624	-0.569	-0.585	-0.604	-0.540
SC_Rn	0.599	0.606	0.394	0.403	0.355	0.410	0.470	0.417	0.490
SC_U	0.205	0.216	0.320	0.303	0.265	0.336	0.347	0.259	0.288
SC_VPD	0.345	0.326	0.528	0.536	0.532	0.506	0.469	0.496	0.432

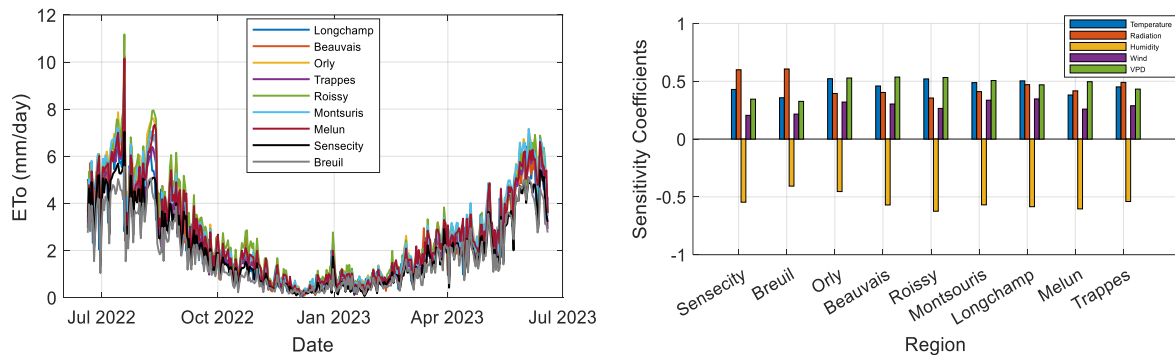


Figure 1. Comparison of PET across all stations (a) and annual SC for all variables across each station (b)

Using lower suburban temperatures may lead to ET_o underestimation and similarly wind speed attenuates from urban structures affects ET_o dynamics, altering stormwater retention in urban green infrastructure. Climate-driven shifts in microclimatic parameters can affect urban drainage responses to extreme events. These factors highlight the need for urban-specific corrections for both spatial and temporal climate differences. One-way sensitivity analysis confirms that T_{max} has the highest sensitivity coefficient, indicating ET_o is predominantly energy-limited year-round. SC_T for Sencecity station is 0.4371; means that every 5% increase in temperature will likely increase the ET_o up to 21.81%. R_n and wind speed positively influence ET_o , with wind playing a moderate but consistent role in aerodynamic resistance. RH_{max} , having a negative SC, though higher in value but lesser impactful than T_{max} , and R_n as the effect of RH_{max} is dominant in winter season where it significantly modulates ET_o by affecting atmospheric moisture availability thus have an overall higher average value along the year (Figure 1b).

Seasonal trends in sensitivity coefficients reveal T_{max} and Rn exert higher control during summer, while wind dominates in winter due to lower temperatures and reduced solar insolation. RH_{max} has a stronger influence in winter when humidity levels are naturally high, suppressing ET_o (Figure 2). Wind speed sensitivity remains stable but varies during transitional seasons due to shifting atmospheric pressure gradients. The negative SC for RH_{max} in winter rises as most of the days in winters have 100% RH_{max} and while applying 25% perturbation to RH_{max} no noticeable effect on VPD is observed. Additionally, under cold conditions, the psychrometric factor becomes dominant, and the already low ET_o baseline amplifies minor fluctuations, leading to higher negative sensitivity values for RH_{max} . These findings highlight the need for climate-adaptive ET_o parameterization in urban drainage models. In the two-way sensitivity analysis, T_{max} and RH_{max} jointly influence ET_o through VPD. The coupled parameters in the sensitivity analysis were selected based on their known interdependence in the evapotranspiration (ET_o) process. Increasing T_{max} while lowering RH_{max} amplifies VPD, driving higher ET_o , whereas increasing RH_{max} dampens this effect. This interaction introduces nonlinearity in ET_o response, highlighting the interdependence of temperature and humidity in evapotranspiration.

This sensitivity analysis shows that, in comparison with other temperature-based evapotranspiration models, FAO-56 is the most effective algorithm to be used in urban drainage modelling as it incorporated all microclimatic variables. But, FAO-56 model, primarily designed for agricultural settings, also bears limitations in urban environments due to heterogeneous surfaces, heat retention, and altered atmospheric exchanges. Increased temperatures and humidity fluctuations further introduce nonlinear responses in urban ET dynamics, requiring climate-adaptive modifications such as urban energy balance corrections to enhance climate-resilient urban drainage models. Also, datasets from remote sensing and satellite imagery can be used for assessing ET_o even if having lower spatial and temporal resolution should be locally verified for application in the urban environment.

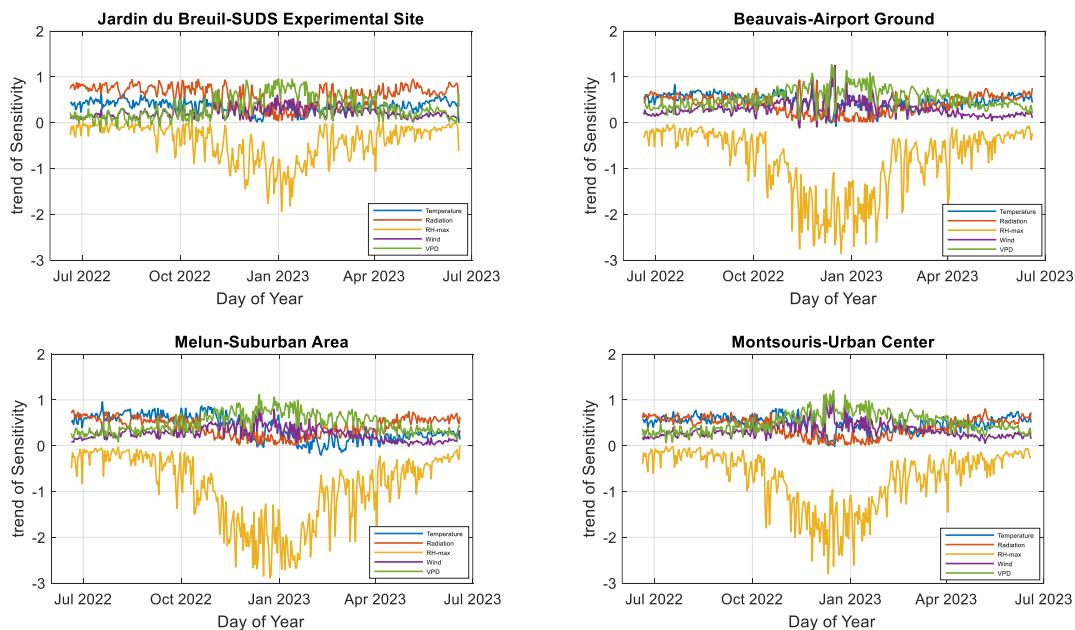


Figure 2. Trend of Sensitivity Coefficient along the year across different stations

Conclusions and future work

The findings underscore the need to incorporate ET_0 variability into urban drainage modelling, as temperature and humidity shifts affect VPD and water balances. This is critical for stormwater management, flood prediction, and green infrastructure design. The use of suburban meteorological data for urban ET_0 estimation presents limitations due to differing conditions. Future efforts should improve ET_0 estimates using urban energy balance and site-specific climate data. Expanding to extreme climate scenarios and varied land-use types will aid model parameterization. While multi-parameter sensitivity analysis was not conducted due to computational complexity, it remains a valuable direction for understanding interactions among climatic drivers.

Acknowledgement

The authors would like to thank the GreenStorm project partners, and especially Ville de Paris, Université Gustave Eiffel and Cerema, for the provision of data on Jardin du Breuil and Sence City.

References

- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome, 300*(9), D05109.
- Emeka, N., Ikenna, O., Okechukwu, M., Chinenye, A., & Emmanuel, E. (2021). Sensitivity of FAO Penman–Monteith reference evapotranspiration (ET_0) to climatic variables under different climate types in Nigeria. *Journal of Water and Climate Change, 12*(3), 858-878.
- Irmak, S., A. S. Irmak, and R. L. Jensen. "Sensitivity analysis of the Penman-Monteith equation parameters in estimating evapotranspiration under humid conditions." *Journal of irrigation and drainage engineering* 132, no. 4 (2006): 431-440.
- Jerszurki, D., de Souza, J. L. M., & Silva, L. D. C. R. (2019). Sensitivity of ASCE-Penman–Monteith reference evapotranspiration under different climate types in Brazil. *Climate dynamics, 53*, 943-956.
- Noto, L.V.; Cipolla, G.; Francipane, A.; Pumo, D. Climate Change in the Mediterranean Basin (Part I): Induced Alterations on Climate Forcings and Hydrological Processes. *Water Resour Manage* 2023, 37, 2287–2305, doi:10.1007/s11269-022-03400-0.
- Sytsma, A., Crompton, O., Panos, C., Thompson, S., & Mathias Kondolf, G. (2022). Quantifying the uncertainty created by non-transferable model calibrations across climate and land cover scenarios: A case study with SWMM. *Water Resources Research, 58*(2), e2021WR031603.