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Spatiotemporal Evaluation and Uncertainty Assessment of Multi-Source Evapotranspiration Products Across Hong Kong: Implications for Mai Po Wetland Water-Balance Monitoring

Francis Quayson ^{1,2,*} , Xiaoli Ding ^{1,2}  and Ishmael Yaw Dadson ³ 

¹ Department of Land Surveying and Geospatial Science, The Hong Kong Polytechnic University, Hong Kong, China; xl.ding@polyu.edu.hk

² Research Institute for Land and Space, The Hong Kong Polytechnic University, Hong Kong, China

³ Department of Geography Education, University of Education, Winneba P.O. Box 25, Ghana; iydadson@uew.edu.gh

* Correspondence: francis.quayson@connect.polyu.hk

Abstract

Accurate evapotranspiration (ET) estimates are essential for hydrological assessment, water-resource management, and wetland conservation, yet global ET products often disagree in heterogeneous coastal environments. This study compared ERA5-Land, GLDAS Noah, TerraClimate, MERRA-2, MOD16A2GF, and PML_V2 across Hong Kong during 2001–2020 and examined their applicability to the Mai Po Marshes. The products were standardized to annual water-depth equivalents and evaluated using descriptive statistics, the Friedman repeated-measures test, Holm-adjusted Wilcoxon signed-rank tests, lag-1 autocorrelation analysis, and standard and Hamed–Rao modified Mann–Kendall tests. Spatial uncertainty was quantified using the inter-product coefficient of variation and summarized by land-cover class. Mean annual ET ranged from 530.09 mm yr^{−1} for GLDAS to 1182.80 mm yr^{−1} for ERA5-Land. Product differences were significant ($\chi^2(5) = 94.74$, $p < 0.001$; Kendall's $W = 0.947$), and all pairwise contrasts remained significant after Holm correction. GLDAS was the only product with a significant increasing trend (Sen's slope = 4.88 mm yr^{−2}, $p < 0.001$), while the remaining products showed no significant trends. Within Mai Po, ET estimates differed among products but showed negligible variation among aggregated wetland habitat classes. The findings support uncertainty-aware, multi-product interpretation for regional ET monitoring and cautious application to compact coastal wetlands.

Keywords: evapotranspiration; Mai Po wetland; ERA5-Land; MOD16A2GF; TerraClimate; GEE



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1. Introduction

Evapotranspiration (ET) regulates the transfer of water and energy between terrestrial surfaces and the atmosphere through soil and open-water evaporation, canopy interception loss, and plant transpiration. It influences watershed water balance, soil-moisture availability, groundwater recharge, vegetation productivity, agricultural water demand, and regional climate processes. Reliable ET estimation is therefore important for hydrological modelling, drought assessment, irrigation planning, ecosystem management, and climate-change adaptation [1–4]. In coastal wetlands, ET also contributes to water-level variability, salinity regulation, vegetation condition, habitat availability, and ecosystem resilience under climatic and anthropogenic pressures [5,6].

Direct measurement of ET remains difficult at regional scales. Eddy-covariance systems, lysimeters, Bowen-ratio energy-balance systems, and scintillometers provide detailed observations, but their spatial footprints are limited and their long-term operation requires substantial financial and technical resources [7,8]. Satellite observations, atmospheric re-analyses, climate datasets, and land-surface models therefore provide essential alternatives for regional and multi-decadal ET monitoring. Cloud-computing platforms such as Google Earth Engine further support these applications by enabling efficient processing of long satellite and reanalysis archives within a consistent analytical environment [9].

Global ET products differ substantially in their physical formulations and input data. MOD16A2GF applies a Penman–Monteith framework using MODIS vegetation and meteorological information, whereas PML_V2 couples water and carbon processes through the Penman–Monteith–Leuning model [4,10]. ERA5-Land and MERRA-2 estimate terrestrial water and energy exchanges through atmospheric and land-surface reanalysis systems [11,12]. GLDAS combines land-surface modelling with meteorological and satellite forcing, while TerraClimate applies a climatologically aided water-balance framework [13,14]. Differences in forcing data, parameterization, spatial resolution, vegetation representation, energy-balance formulation, and quality-control procedures can therefore produce substantial discrepancies in ET magnitude, temporal variability, and spatial distribution [2,3,15].

Previous multi-product evaluations have mainly examined large river basins, continental domains, agricultural regions, forests, and extensive dryland environments. Studies conducted across major basins and ecological regions have consistently shown that no single ET product performs uniformly under all climatic and land-cover conditions [15–19]. Product behavior depends on climate, vegetation structure, surface-water availability, topography, and the quality of meteorological forcing. Large-area studies, however, do not fully represent the challenges encountered in compact coastal regions where urban surfaces, forests, reservoirs, agricultural land, estuaries, wetlands, and open water occur within short distances.

Hong Kong provides an appropriate setting for such an evaluation because it combines pronounced environmental heterogeneity with a relatively small geographical extent. Its humid subtropical monsoon climate, mountainous terrain, dense urban development, extensive coastal interfaces, reservoirs, forests, and protected wetlands create strong local gradients in available energy, soil moisture, vegetation activity, and atmospheric demand. These conditions also increase mixed-pixel effects and scale mismatches when coarse global ET products are applied to local environmental assessment.

The Mai Po–Inner Deep Bay Ramsar Wetland provides a particularly important case study. The wetland contains mangroves, mudflats, reedbeds, gei wai, fishponds, marshes, and open-water habitats that support internationally important migratory waterbird populations along the East Asian–Australasian Flyway. Its ecological condition depends strongly on water-level management and hydrological exchange. However, the wetland is small relative to several global ET grids, meaning that some products represent it through mixed regional pixels rather than habitat-specific observations. Even nominally finer products may lose local information when harmonized to a common comparison grid. Regional evaluation across Hong Kong is therefore necessary before interpreting ET estimates for Mai Po.

Three research gaps motivate this study. First, relatively few ET intercomparisons have focused on compact coastal metropolitan regions containing highly fragmented urban, forest, wetland, and open-water surfaces. Second, limited attention has been given to how inter-product uncertainty varies among land-cover classes in such environments. Third, the spatial suitability of global ET products for internationally protected wetlands is often discussed without explicitly evaluating the effects of valid-pixel support, resolution

mismatch, and common-grid aggregation. These gaps limit confidence in the use of global ET products for coastal water-balance monitoring and wetland management.

This study evaluates six widely used ET products—ERA5-Land, GLDAS Noah, Terra-Climate, MERRA-2, MOD16A2GF, and PML_V2—across Hong Kong during 2001–2020. The objectives are to: (1) compare their long-term spatial patterns and annual ET magnitudes; (2) test whether annual estimates differ significantly among products; (3) evaluate long-term trends while accounting for serial autocorrelation; (4) quantify inter-product spatial uncertainty and its variation among major land-cover classes; and (5) assess the implications of product resolution and spatial aggregation for ET interpretation within the Mai Po Marshes.

The study makes four contributions. First, it provides a multi-product ET assessment for a compact and environmentally heterogeneous coastal metropolitan region. Second, it integrates repeated-measures statistical testing, autocorrelation diagnostics, modified trend analysis, and spatial uncertainty assessment within a common processing framework. Third, it quantitatively links inter-product uncertainty to major land-cover classes rather than relying only on visual interpretation of an uncertainty map. Fourth, it distinguishes regional ET applicability from habitat-scale wetland interpretation by examining the spatial support and aggregation limitations of the six products. These contributions provide an uncertainty-aware basis for selecting and interpreting ET products in Hong Kong and comparable coastal environments.

2. Materials and Methods

2.1. Study Area

Hong Kong is located on the southern coast of China between 22°08′–22°35′ N and 113°49′–114°31′ E, occupying approximately 1106 km² (Figure 1). The territory comprises Hong Kong Island, the Kowloon Peninsula, the New Territories, and more than 260 offshore islands. The landscape is characterized by rugged mountains, lowland plains, extensive coastal environments, reservoirs, wetlands, and highly urbanized districts, producing substantial spatial heterogeneity over relatively short distances.

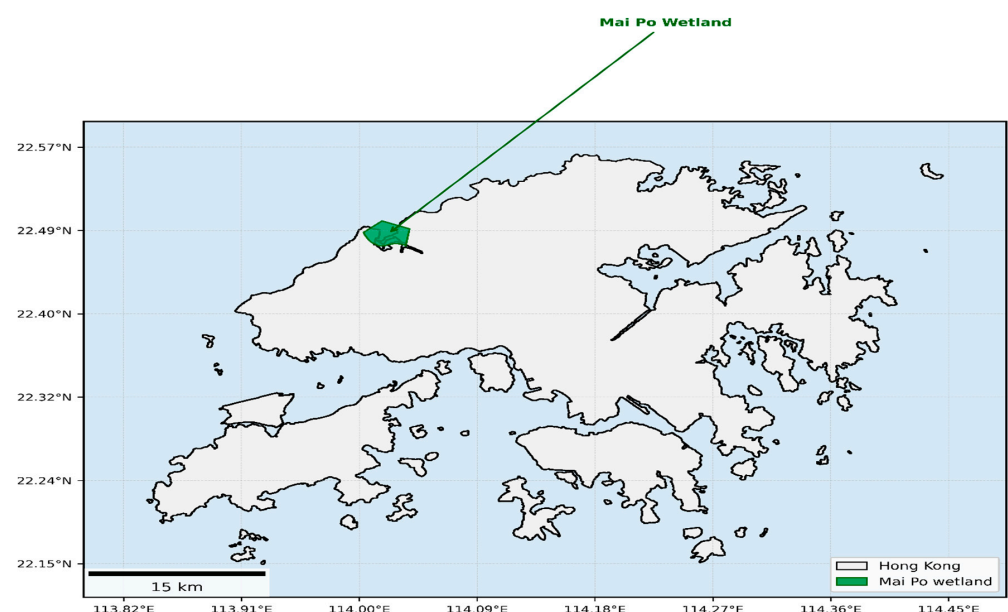


Figure 1. Location of Hong Kong and the Mai Po Marshes. The figure shows the geographical location of Hong Kong within southern China and the location of the Mai Po–Inner Deep Bay Ramsar Wetland used for the wetland-scale evaluation.

Hong Kong experiences a humid subtropical monsoon climate (Köppen Cwa) characterized by warm, humid summers and mild, relatively dry winters. Mean annual air temperature ranges from approximately 22 to 24 °C, while annual precipitation exceeds 2300 mm, with nearly 80% occurring between May and September under the influence of the East Asian summer monsoon. High atmospheric humidity, abundant rainfall, and pronounced seasonal variability strongly influence terrestrial evapotranspiration and regional water availability [1–3].

Vegetation consists primarily of secondary forests, shrublands, grasslands, mangroves, freshwater wetlands, reservoirs, and urban green spaces. Forested hills dominate much of the central and eastern parts of the territory, whereas intensive urban development is concentrated along the northern coastline of Hong Kong Island and Kowloon. Coastal wetlands, including the internationally important Mai Po Nature Reserve, provide valuable habitats for migratory waterbirds and represent one of the largest remaining wetland ecosystems within the Pearl River Delta [6].

The combination of steep topography, diverse land-cover types, and rapid transitions between natural and urban environments makes Hong Kong an ideal location for evaluating the performance of global evapotranspiration datasets. These characteristics present significant challenges for coarse-resolution Earth observation products because individual pixels frequently encompass multiple land-cover types, increasing uncertainty in evapotranspiration estimation. Consequently, Hong Kong provides an appropriate testbed for assessing inter-product consistency across regional landscapes and for examining the applicability of global evapotranspiration products to heterogeneous coastal wetlands.

2.2. Evapotranspiration Products

Six widely used global evapotranspiration (ET) products representing different modelling philosophies were evaluated in this study: ERA5-Land, GLDAS Noah, TerraClimate, MERRA-2, MOD16A2GF, and PML_V2 (Table 1). These datasets were selected because they provide continuous long-term observations covering the study period (2001–2020), are freely available through Google Earth Engine, and represent a broad range of physically based reanalysis systems, land-surface models, climate water-balance models, and satellite-driven evapotranspiration algorithms. Their methodological diversity provides a robust basis for evaluating structural uncertainty associated with regional ET estimation.

Table 1. Characteristics of the evapotranspiration products used in this study.

Product	ET Approach	Main Forcing Data	Spatial Resolution	Main Assumption or Limitation
ERA5-Land	Land-surface reanalysis	ECMWF atmospheric reanalysis	~9 km	Coarse resolution smooths heterogeneous surfaces
GLDAS Noah	Land-surface model	Meteorological observations and satellite assimilation	~25 km	Mixed pixels limit local coastal applications
TerraClimate	Climate water-balance model	Climatic observations and water-balance modelling	~4 km	Empirical water-balance assumptions simplify local processes
MERRA-2	Atmospheric reanalysis	GEOS atmospheric assimilation	~50 km	Very coarse resolution limits local-scale interpretation
MOD16A2GF	Satellite Penman–Monteith algorithm	MODIS vegetation and meteorological data	500 m	Sensitive to cloud contamination and vegetation inputs
PML_V2	Penman–Monteith–Leuning model	MODIS observations and meteorological forcing	500 m	Sensitive to vegetation and carbon-cycle parameterization

ERA5-Land is the land component of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis system and estimates evapotranspiration

through physically based simulation of land–atmosphere energy and water exchanges driven by assimilated meteorological observations [11]. GLDAS Noah is a land-surface modelling system developed by the National Aeronautics and Space Administration (NASA) that combines meteorological observations and satellite-derived information within the Noah land-surface model to simulate terrestrial water and energy fluxes [13]. TerraClimate estimates evapotranspiration using a climate water-balance approach that integrates high-resolution climatological observations with reference evapotranspiration calculations [14]. MERRA-2 is NASA’s modern atmospheric reanalysis that derives surface water and energy fluxes through assimilation of atmospheric observations within the Goddard Earth Observing System (GEOS) modelling framework [12].

The two satellite-derived products apply modified Penman–Monteith formulations but differ in their representation of vegetation processes. MOD16A2GF estimates evapotranspiration using remotely sensed vegetation properties together with meteorological forcing within the Penman–Monteith framework [9]. In contrast, PML_V2 applies the Penman–Monteith–Leuning model, which explicitly represents canopy transpiration, soil evaporation, canopy interception, and vegetation carbon assimilation [10]. Including products based on fundamentally different modelling approaches enables uncertainty arising from algorithm structure, forcing datasets, and parameterization schemes to be evaluated rather than relying on products derived from similar methodologies. The overall methodological workflow adopted in this study is summarized in Figure 2.

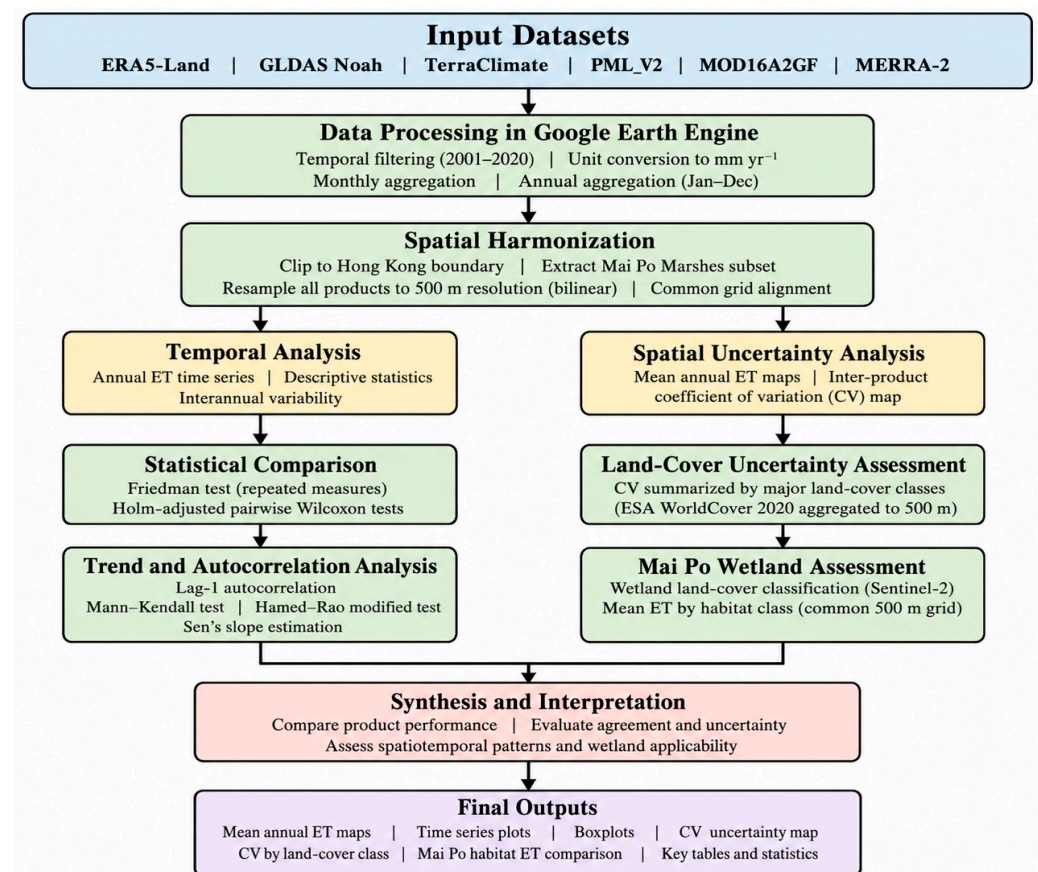


Figure 2. Methodological workflow for the evaluation of six multi-source evapotranspiration products across Hong Kong and the Mai Po wetland subset for the period 2001–2020.

All products were converted to annual evapotranspiration totals expressed in mm yr^{-1} to ensure direct comparison. Because native spatial resolutions ranged from 500 m to approximately 50 km, all datasets were subsequently harmonized to a common analysis

grid before spatial comparison and statistical evaluation. This harmonization ensured that differences among products reflected modelling approaches rather than inconsistencies associated with spatial resolution, map projection, or pixel alignment.

2.3. Data Processing and Spatial Harmonization

All evapotranspiration (ET) products were accessed through Google Earth Engine (GEE) and processed over the period January 2001 to December 2020. Monthly ET products (ERA5-Land, GLDAS Noah, TerraClimate, and MERRA-2) were aggregated to annual totals by summing monthly evapotranspiration values for each calendar year. The 8-day products (MOD16A2GF and PML_V2) were first aggregated to monthly totals and subsequently summed to produce annual ET. All datasets were converted to a common unit of millimeters per year (mm yr^{-1}) to ensure direct comparison among products.

The six ET products differ substantially in native spatial resolution, ranging from 500 m for MOD16A2GF and PML_V2 to approximately 50 km for MERRA-2. Direct pixel-by-pixel comparison among products is therefore inappropriate because differences may reflect variations in spatial support rather than actual evapotranspiration estimates. To overcome this limitation, all datasets were projected to the World Geodetic System 1984 (WGS 84) coordinate reference system and harmonized to a common 500 m analysis grid covering the entire Hong Kong territory.

The 500 m analysis grid was selected because it preserves the native resolution of the highest-resolution satellite products while providing a consistent spatial framework for inter-product comparison. Importantly, harmonization to a common grid does not increase the intrinsic spatial information contained within coarse-resolution products. Instead, the procedure provides common spatial support so that differences among datasets primarily reflect variations in model structure, forcing data, and algorithm design rather than inconsistencies associated with projection, pixel alignment, or grid geometry.

Continuous ET datasets were resampled using bilinear interpolation, which preserves gradual spatial variation appropriate for continuous environmental variables. In contrast, categorical datasets, including land-cover information, were resampled using the nearest-neighbor or modal (majority) method to preserve discrete class identities and avoid generating artificial mixed classes.

Following harmonization, long-term mean annual ET maps were produced by averaging the twenty annual ET layers for each product:

$$\bar{ET} = \frac{1}{n} \sum_{i=1}^n ET_i \quad (1)$$

where $\bar{ET}$ is the long-term mean annual evapotranspiration (mm yr^{-1}), ET_i represents the annual ET for year i , and n is the total number of years (20).

Annual regional mean ET values were subsequently extracted from each dataset for statistical comparison and temporal trend analysis. All spatial preprocessing, raster calculations, and map generation were undertaken using Google Earth Engine (GEE; <https://earthengine.google.com>; accessed 2 June 2026). Statistical analyses were performed using Python 3.12 (Python Software Foundation, Wilmington, DE, USA) with the SciPy (v1.15), NumPy (v2.4), pandas (v2.2), and matplotlib (v3.11.0) libraries.

2.4. Statistical and Spatial Uncertainty Analysis

Descriptive statistics were first calculated for each evapotranspiration product to summarize annual ET characteristics over the 2001–2020 study period. These included the mean, minimum, maximum, standard deviation (SD), and coefficient of variation (CV). The descriptive statistics provided an initial assessment of differences in ET magnitude and temporal variability among the six products.

Because each ET product represents repeated measurements of the same study area over identical years, differences among products were evaluated using the Friedman repeated-measures test, a non-parametric alternative to repeated-measures analysis of variance that does not require normally distributed observations [20]. The strength of agreement among products was quantified using Kendall's coefficient of concordance (W) [21]. When the Friedman test indicated statistically significant differences, pairwise Wilcoxon signed-rank tests with Holm-adjusted p -values were performed to identify which product pairs differed significantly while controlling the family-wise error rate associated with multiple comparisons [22,23].

Long-term temporal trends were evaluated using the Mann–Kendall trend test, while the magnitude of change was quantified using the Theil–Sen slope estimator [24,25]. Before trend analysis, lag-1 autocorrelation coefficients were calculated for each ET product to determine whether serial dependence could influence the significance of the Mann–Kendall statistic. Where significant autocorrelation was detected, the Hamed–Rao modified Mann–Kendall test was applied to provide corrected significance estimates while maintaining the robustness of the non-parametric procedure [26].

Spatial uncertainty among the six ET products was quantified using the coefficient of variation (CV) calculated from the long-term mean annual ET estimates:

$$CV(\%) = \frac{\sigma}{\mu} \times 100 \quad (2)$$

where σ is the standard deviation and μ is the mean ET across the six products. Lower CV values indicate stronger agreement among products, whereas higher CV values indicate greater inter-product uncertainty.

To examine whether uncertainty varied among landscape types, land-cover information was obtained from the ESA WorldCover 2020 dataset at 10 m spatial resolution [27]. The original land-cover classes were aggregated to the common 500 m analysis grid using the modal class. Mean CV values were subsequently calculated for the major land-cover classes represented within Hong Kong, including tree cover, grassland, built-up areas, mangroves, and permanent water bodies. This analysis provided a quantitative assessment of how landscape characteristics influence uncertainty in multi-product ET estimation.

All statistical analyses were conducted in Python, whereas spatial analyses and raster processing were performed in Google Earth Engine. Statistical significance was assessed at $p < 0.05$ throughout the study.

2.5. Mai Po Wetland Assessment

The suitability of the six global evapotranspiration products for wetland-scale applications was evaluated using the Mai Po Nature Reserve, a Ramsar-listed coastal wetland located in northwestern Hong Kong. Mai Po contains an extensive mosaic of mangroves, mudflats, marshes, open water, and wetland vegetation, making it an appropriate site for assessing the influence of spatial resolution on ET estimation within heterogeneous coastal ecosystems.

Land-cover information for Mai Po was derived from Sentinel-2 Level-2A surface reflectance imagery acquired during 2020 [28]. Images affected by excessive cloud cover were excluded, and the remaining observations were cloud-masked using the Sentinel-2 Scene Classification Layer (SCL) together with the QA60 quality-assurance band before generating a median image composite.

Three spectral indices were calculated to facilitate wetland habitat classification. The Normalized Difference Vegetation Index (NDVI) [29] was computed as

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (3)$$

The Normalized Difference Water Index (NDWI) [30] was calculated as

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (4)$$

The Normalized Difference Built-up Index [31] (NDBI) was calculated as

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR} \quad (5)$$

where *NIR*, *Red*, *Green*, and *SWIR* represent the near-infrared, red, green, and shortwave-infrared Sentinel-2 spectral bands, respectively.

The combined spectral information was used to classify the Mai Po wetland into four aggregated habitat classes: wetland vegetation, open water, mudflat or bare wetland, and built-up or dry surface. The classified land-cover map was subsequently aggregated to the common 500 m analysis grid using the modal class to ensure direct correspondence with the harmonized ET products.

Mean annual evapotranspiration for each product and habitat class was calculated as

$$\bar{ET}_{p,c} = \frac{1}{n_c} \sum_{i=1}^{n_c} ET_{p,i} \quad (6)$$

where $\bar{ET}_{p,c}$ is the mean annual *ET* for product *p* within habitat class *c*, $ET_{p,i}$ is the annual *ET* value for grid cell *i*, and n_c is the number of valid common-grid cells belonging to habitat class *c*.

Only grid cells containing valid observations for all six ET products were retained to ensure that comparisons were based on identical spatial locations. This common-grid approach eliminated inconsistencies caused by unequal spatial coverage and allowed direct comparison among products.

The native spatial resolution of each ET product was explicitly considered during interpretation of the wetland results. Harmonization to a common 500 m grid provided consistent spatial alignment but did not increase the effective spatial information contained within products having substantially coarser native resolutions. Consequently, the wetland analysis evaluates inter-product consistency rather than habitat-scale accuracy. The resulting ET estimates therefore represent regional-scale atmospheric water loss over the Mai Po wetland rather than independent measurements of individual wetland habitats.

The Mai Po assessment complements the regional Hong Kong analysis by examining the influence of spatial scale on evapotranspiration estimation and provides practical guidance for selecting appropriate global ET products for regional hydrological studies and coastal wetland applications.

3. Results

3.1. Spatial Distribution of Mean Annual Evapotranspiration

The six evapotranspiration (ET) products exhibited similar broad spatial patterns across Hong Kong during the 2001–2020 study period but differed considerably in the magnitude of estimated annual ET (Figure 3). Higher ET values were generally concentrated in forested uplands and densely vegetated areas, whereas relatively lower values occurred over urban surfaces, exposed coastal areas, and regions with sparse vegetation. Despite these common spatial characteristics, substantial differences were evident among the products, reflecting variations in model formulation, forcing data, and spatial resolution.

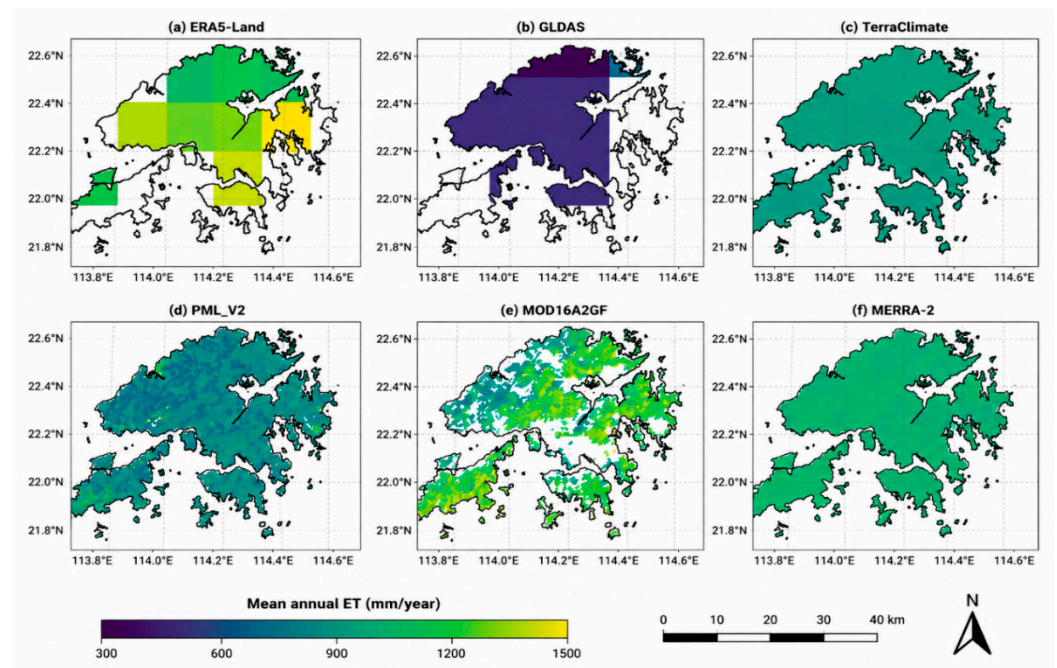


Figure 3. Spatial distribution of long-term mean annual evapotranspiration derived from (a) ERA5-Land, (b) GLDAS Noah, (c) TerraClimate, (d) PML_V2, (e) MOD16A2GF, and (f) MERRA-2 across Hong Kong during 2001–2020. All products were expressed in mm yr^{-1} and displayed using a common colour scale. White areas indicate masked or unavailable observations.

ERA5-Land produced the highest mean annual ET across most of Hong Kong, followed by MERRA-2 and TerraClimate. In contrast, GLDAS consistently generated the lowest ET estimates, while MOD16A2GF and PML_V2 produced intermediate values. Although the absolute magnitudes differed, the products consistently identified similar zones of relatively high and low evapotranspiration, indicating agreement in the general spatial distribution of ET despite differences in estimated water-loss rates.

The influence of spatial resolution was particularly evident when comparing the products. The finer-resolution MOD16A2GF and PML_V2 datasets captured greater local spatial variability, especially along coastlines, reservoirs, and fragmented landscapes. Conversely, the coarser reanalysis products, particularly MERRA-2 and GLDAS, produced smoother spatial patterns because each grid cell represented a much larger area. ERA5-Land provided a compromise between regional continuity and spatial detail, producing relatively smooth but geographically coherent ET distributions.

Overall, the spatial comparison demonstrates that the six products consistently reproduced the principal evapotranspiration gradients across Hong Kong while differing substantially in ET magnitude. These systematic differences highlight the importance of quantitative statistical comparison before selecting an appropriate product for hydrological or ecological applications.

3.2. Descriptive Comparison of Annual Evapotranspiration

Annual evapotranspiration differed substantially among the six products over the 2001–2020 period (Figure 4; Table 2). Mean annual ET ranged from $530.09 \text{ mm yr}^{-1}$ for GLDAS to $1182.80 \text{ mm yr}^{-1}$ for ERA5-Land, representing a difference of more than 650 mm yr^{-1} . MERRA-2 and TerraClimate produced relatively high annual ET estimates of $1084.63 \text{ mm yr}^{-1}$ and $1030.36 \text{ mm yr}^{-1}$, respectively, whereas PML_V2 ($776.37 \text{ mm yr}^{-1}$) and MOD16A2GF ($671.77 \text{ mm yr}^{-1}$) occupied an intermediate range.

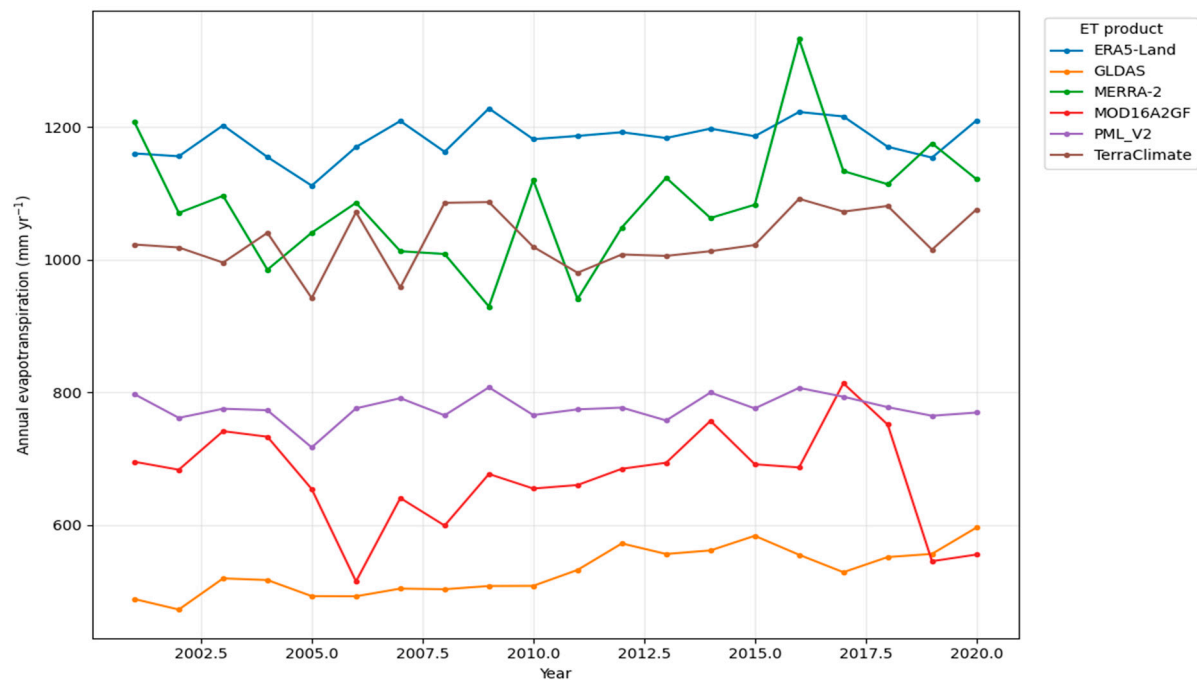


Figure 4. Annual evapotranspiration estimated by ERA5-Land, GLDAS Noah, MERRA-2, MOD16A2GF, PML_V2, and TerraClimate across Hong Kong during 2001–2020. The products exhibited similar interannual variability but differed substantially in the magnitude of annual evapotranspiration.

Table 2. Descriptive statistics of annual evapotranspiration (mm yr^{-1}) across Hong Kong during 2001–2020.

Product	Mean	Minimum	Maximum	SD	CV (%)
ERA5-Land	1182.80	1111.73	1228.08	28.59	2.42
GLDAS Noah	530.09	472.61	596.08	34.77	6.56
MERRA-2	1084.63	929.38	1332.47	92.29	8.51
MOD16A2GF	671.77	515.00	813.71	74.48	11.09
PML_V2	776.37	717.06	807.62	20.42	2.63
TerraClimate	1030.36	942.18	1091.82	44.11	4.28

Interannual variability also differed among products. MOD16A2GF exhibited the largest relative variability, with a coefficient of variation of 11.09%, followed by MERRA-2 (8.51%) and GLDAS (6.56%). In contrast, ERA5-Land (2.42%) and PML_V2 (2.63%) showed comparatively stable annual ET estimates throughout the study period. TerraClimate displayed moderate variability, with a coefficient of variation of 4.28%.

The annual ranges further illustrate the differences among products. ERA5-Land varied from 1111.73 to 1228.08 mm yr^{-1} , while GLDAS ranged between 472.61 and 596.08 mm yr^{-1} . MERRA-2 exhibited the widest absolute range (929.38–1332.47 mm yr^{-1}), whereas PML_V2 showed the smallest range (717.06–807.62 mm yr^{-1}). These differences demonstrate that the products differ not only in average ET magnitude but also in their representation of interannual variability.

Overall, the descriptive statistics indicate that although all products capture long-term evapotranspiration over Hong Kong, considerable systematic differences exist among them. These differences necessitate formal statistical comparison to determine whether the observed variation is statistically significant.

3.3. Statistical Comparison of Evapotranspiration Products

The Friedman repeated-measures test revealed highly significant differences among the six evapotranspiration products over the 2001–2020 study period ($\chi^2 = 94.74$, $df = 5$, $p < 0.001$), demonstrating that annual ET estimates differed systematically among products (Figure 5; Table 3). The corresponding Kendall's coefficient of concordance ($W = 0.947$) indicated a very large effect size and strong consistency in the relative ranking of the products across the 20 years.

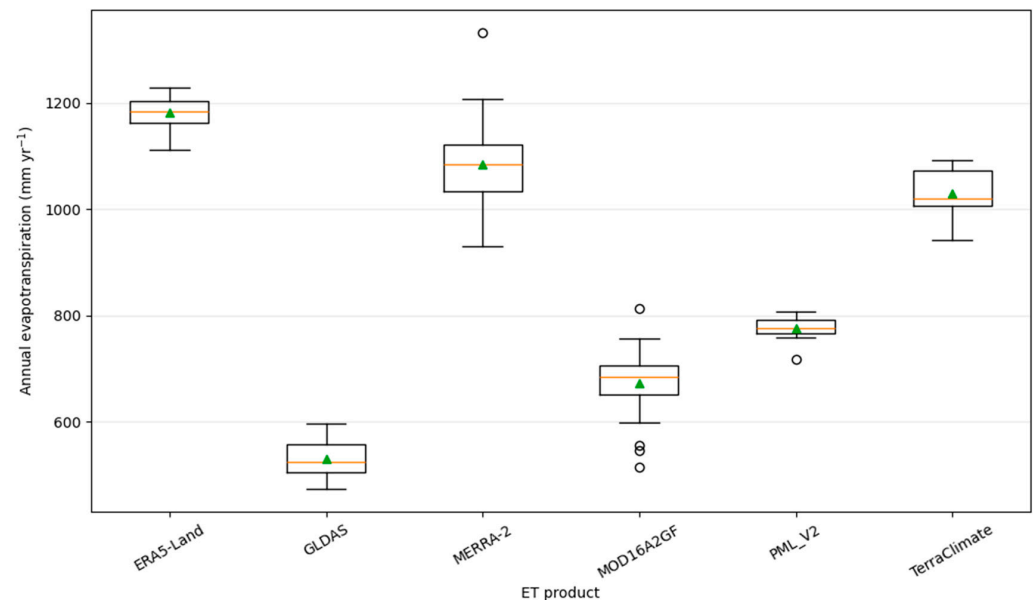


Figure 5. Distribution of annual evapotranspiration estimates derived from the six evaluated products during 2001–2020. Boxes represent the interquartile range (IQR), the horizontal line indicates the median, triangles denote the mean, whiskers extend to $1.5 \times \text{IQR}$, and circles represent outliers.

Table 3. Friedman repeated-measures test comparing annual evapotranspiration among the six products.

Test	χ^2	df	<i>p</i> -Value	Number of Years	Number of Products	Kendall's W	Effect Size
Friedman repeated-measures test	94.74	5	<0.001	20	6	0.947	Large

Post hoc pairwise Wilcoxon signed-rank tests with Holm adjustment confirmed that all 15 product pairs differed significantly (Supplementary Table S1). ERA5-Land produced significantly higher annual ET than GLDAS, MOD16A2GF, PML_V2, TerraClimate, and MERRA-2. Similarly, GLDAS consistently estimated significantly lower ET than all other products. MERRA-2 generated significantly higher ET than MOD16A2GF, PML_V2, and TerraClimate, while MOD16A2GF remained significantly lower than both PML_V2 and TerraClimate. The only comparatively small difference occurred between MERRA-2 and TerraClimate, although this comparison also remained statistically significant after Holm correction ($p = 0.015$).

The strong statistical separation among products confirms that the observed differences in annual ET were not attributable to random year-to-year variation but instead reflected systematic differences in product formulation, forcing data, and modelling approaches. Consequently, the six products should not be considered interchangeable for regional hydrological applications.

3.4. Temporal Trends and Autocorrelation

Lag-1 autocorrelation analysis indicated that only GLDAS exhibited statistically significant serial correlation ($r = 0.770$, $p < 0.001$), whereas the remaining five products showed weak and non-significant autocorrelation (Table 4). Consequently, both the standard Mann–Kendall test and the Hamed–Rao modified Mann–Kendall test were applied to ensure robust trend detection.

Table 4. Lag-1 autocorrelation and Hamed–Rao modified Mann–Kendall trend results.

Product	Lag-1 r	Lag-1 p	Sen's Slope (mm yr ^{−2})	Hamed–Rao Z	p -Value	Trend
ERA5-Land	0.092	0.709	2.36	1.65	0.098	No trend
GLDAS Noah	0.770	<0.001	4.88	3.80	<0.001	Increasing
MERRA-2	0.194	0.426	5.51	1.59	0.112	No trend
MOD16A2GF	0.370	0.119	0.81	0.27	0.790	No trend
PML_V2	−0.099	0.686	0.19	0.79	0.431	No trend
TerraClimate	−0.091	0.710	2.62	1.40	0.163	No trend

The modified Mann–Kendall analysis identified GLDAS as the only product exhibiting a statistically significant increasing trend during 2001–2020. The estimated Theil–Sen slope was 4.88 mm yr^{−2}, with a modified Mann–Kendall Z -value of 3.80 ($p < 0.001$), indicating a persistent increase in annual evapotranspiration throughout the study period. In contrast, ERA5-Land, MERRA-2, MOD16A2GF, PML_V2, and TerraClimate showed no statistically significant long-term trends after accounting for serial correlation.

Although several products exhibited positive Sen's slopes, their trend magnitudes were relatively small and did not reach statistical significance. For example, ERA5-Land showed an estimated increase of 2.36 mm yr^{−2}, while TerraClimate exhibited a slope of 2.62 mm yr^{−2}. MOD16A2GF and PML_V2 displayed only minor positive changes over time, indicating relatively stable long-term behavior.

Overall, the trend analysis suggests that the six products differ primarily in the magnitude of estimated evapotranspiration rather than in their representation of long-term temporal change. The significant increase detected only in GLDAS further demonstrates that long-term ET trends may depend on the underlying modelling framework and forcing datasets.

3.5. Spatial Uncertainty Across Land-Cover Classes

Spatial uncertainty among the six evapotranspiration products was quantified using the coefficient of variation (CV) calculated from the long-term mean annual ET estimates (Figure 6). The CV map indicates substantial inter-product uncertainty across Hong Kong, with uncertainty varying spatially according to differences in product agreement. Lower CV values represent stronger agreement among the six products, whereas higher values indicate greater disagreement. The analysis was performed on a harmonized 500 m analysis grid after all datasets were projected to a common coordinate reference system and spatially aligned.

The land-cover analysis confirmed that uncertainty differed only slightly among the major surface classes (Table 5; Figure 7). Mean CV values ranged from 28.33% over permanent water bodies to 29.12% over built-up areas. Grassland recorded a mean CV of 29.09%, tree cover 28.95%, and mangroves 28.85%. Because the difference between the highest and lowest class means was less than one percentage point, all represented classes were classified as having high inter-product uncertainty.

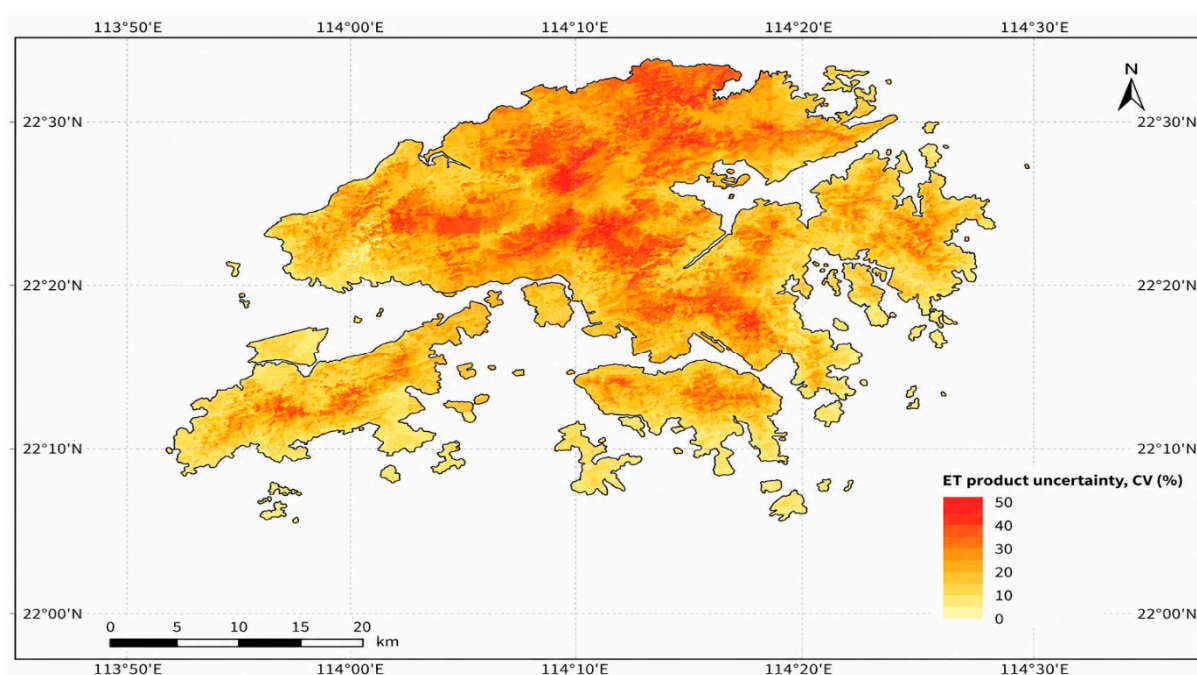


Figure 6. Spatial distribution of inter-product uncertainty across Hong Kong expressed as the coefficient of variation (CV) of the six long-term mean annual evapotranspiration products (2001–2020). Lower CV values indicate stronger agreement among the evapotranspiration products, whereas higher values indicate greater inter-product uncertainty.

Table 5. Inter-product uncertainty by major land-cover class across Hong Kong.

Land-Cover Class	Mean CV (%)	Median CV (%)	CV Range (%)	Uncertainty Level
Built-up	29.115	29.118	29.113–29.118	High
Grassland	29.090	29.090	29.090–29.090	High
Tree cover	28.946	29.039	28.443–29.078	High
Mangroves	28.845	28.845	28.845–28.845	High
Permanent water bodies	28.331	28.063	27.972–28.816	High

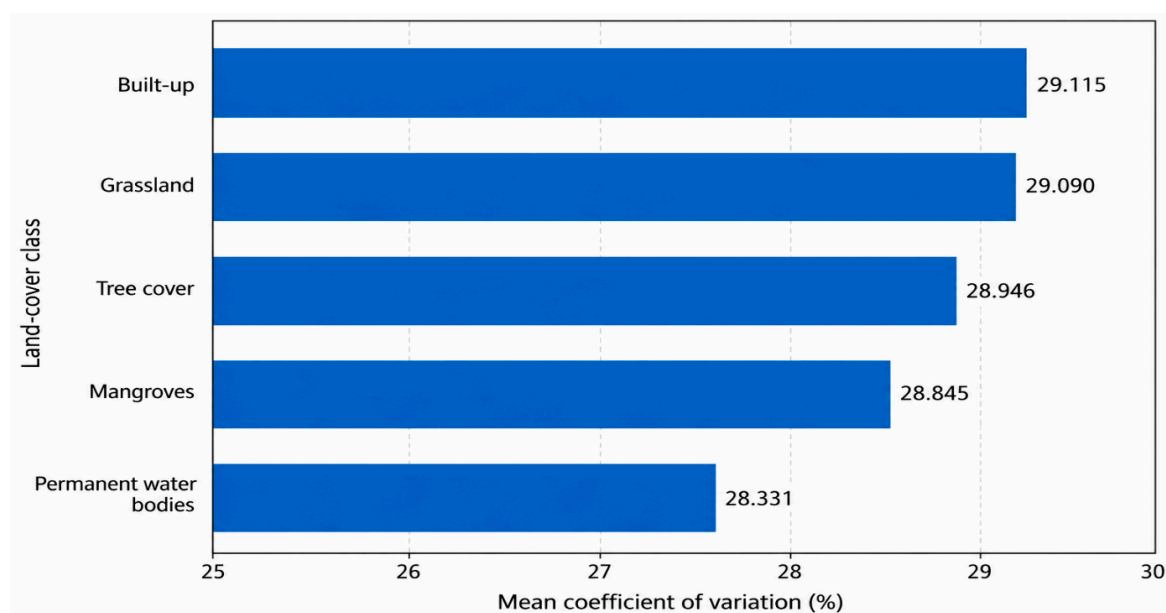


Figure 7. Mean coefficient of variation in the six evapotranspiration products across the major land-cover classes represented in Hong Kong.

Built-up areas and grassland showed the highest mean CV values, although these classes were represented by relatively few common-grid cells. Tree cover occupied the largest proportion of the study area and still exhibited a high mean CV, confirming that disagreement was not simply caused by limited spatial representation. Permanent water bodies produced the lowest mean CV, but the value remained high and therefore did not indicate strong product agreement.

The narrow variation among land-cover classes suggests that product-related factors exerted a stronger influence on uncertainty than land cover itself. Differences in model structure, meteorological forcing, parameterization, vegetation representation, and native spatial resolution likely contributed to the systematic divergence among products. The CV map should therefore be interpreted as a measure of structural inter-product uncertainty rather than as a direct indicator of land-cover-specific ET error.

Overall, the analysis shows that no major land-cover class consistently produced close agreement among the six ET products. Regional ET assessments across Hong Kong should therefore report uncertainty alongside mean estimates and avoid treating any individual product as an absolute reference.

3.6. Representation of the Mai Po Marshes

The applicability of the six evapotranspiration products to the Mai Po Marshes was assessed by comparing mean annual ET among the aggregated wetland land-cover classes. The products differed markedly in ET magnitude, but each product showed only minimal variation among mudflat or bare wetland, open water, and wetland vegetation (Table 6a; Figure 8).

Table 6. (a) Mean annual evapotranspiration by aggregated Mai Po land-cover class. (b) Number of valid common-grid cells used for the Mai Po habitat analysis.

(a)						
Land-Cover Class	ERA5-Land	GLDAS	MERRA-2	MOD16A2GF	PML_V2	TerraClimate
Mudflat or bare wetland	1166.39	491.41	1103.50	625.81	778.44	1032.13
Open water	1165.58	490.42	1104.56	624.81	778.51	1032.21
Wetland vegetation	1166.11	490.67	1103.77	625.66	778.49	1032.16
Built-up or dry surface	—	—	—	—	—	—
(b)						
Land-Cover Class	ERA5-Land	GLDAS Noah	MERRA-2	MOD16A2GF	PML_V2	TerraClimate
Mudflat or bare wetland	3	3	3	3	3	3
Open water	2	2	2	2	2	2
Wetland vegetation	18	18	18	18	18	18
Built-up or dry surface	0	0	0	0	0	0

ERA5-Land produced the highest estimates, ranging from 1165.58 to 1166.39 mm yr^{−1} across the three wetland classes. MERRA-2 produced similarly high values of approximately 1103.50–1104.56 mm yr^{−1}, followed by TerraClimate at approximately 1032.13–1032.21 mm yr^{−1}. PML_V2 produced intermediate values near 778.44–778.51 mm yr^{−1}, whereas MOD16A2GF and GLDAS produced lower estimates of approximately 624.81–625.81 mm yr^{−1} and 490.42–491.41 mm yr^{−1}, respectively (Table 6a).

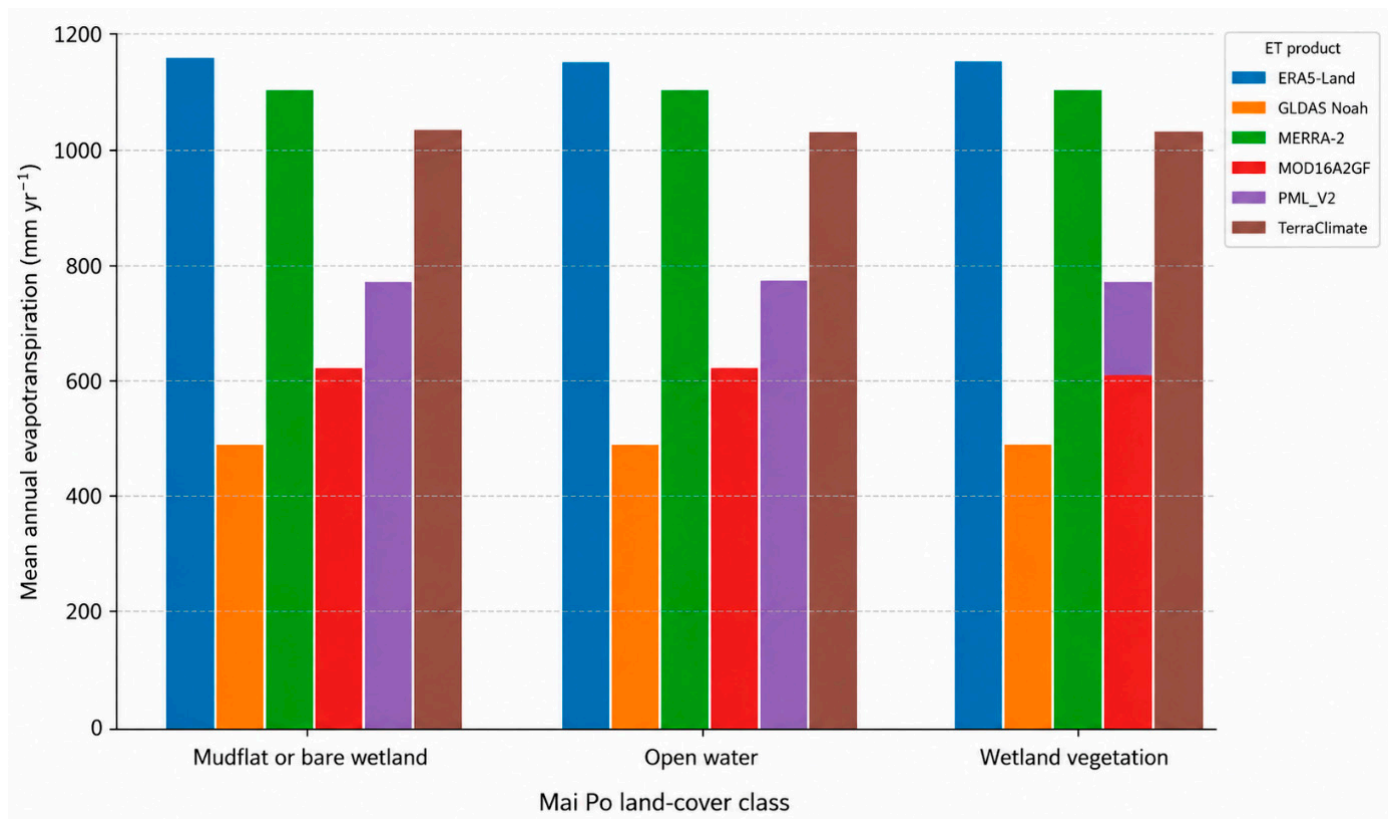


Figure 8. Mean annual evapotranspiration estimated by ERA5-Land, GLDAS Noah, MERRA-2, MOD16A2GF, PML_V2, and TerraClimate for the three major Mai Po wetland habitat classes (mudflat or bare wetland, open water, and wetland vegetation). Although substantial differences exist among products, evapotranspiration estimates within individual products vary only slightly across habitat classes. No valid common-grid pixels were assigned to the built-up or dry-surface class after spatial harmonization; therefore, this class was excluded from the figure.

Within each product, differences among habitat classes were generally less than 1 mm yr^{-1} . For example, ERA5-Land differed by only 0.81 mm yr^{-1} between mudflat and open water, while PML_V2 differed by less than 0.1 mm yr^{-1} across all three classes. These negligible differences show that the harmonized products represented Mai Po largely as a spatially uniform ET surface after aggregation to the common grid (Table 6a; Figure 8).

The number of valid common-grid cells used in the comparison varied among habitat classes but was identical across the six products because only cells containing valid observations for all datasets were retained. Wetland vegetation had the greatest spatial representation, with 18 valid cells per product, while mudflat or bare wetland and open water were represented by three and two cells, respectively. No valid cells were assigned to the built-up or dry-surface class after aggregation (Table 6b).

The similarity among habitat-specific estimates does not imply that actual evapotranspiration is uniform across Mai Po. Rather, it reflects the limited effective spatial information of the products relative to the size and internal heterogeneity of the wetland. Resampling coarse datasets to 500 m aligned the products spatially but did not create new local information. Consequently, the products are suitable for broad regional ET assessment over the Mai Po area but cannot reliably resolve habitat-scale differences.

4. Discussion

4.1. Inter-Product Differences and Temporal Behavior

The six evapotranspiration products reproduced broadly similar spatial patterns across Hong Kong but differed substantially in annual ET magnitude. ERA5-Land consistently produced the highest estimates, whereas GLDAS Noah produced the lowest. MERRA-2 and TerraClimate occupied the upper-middle range, while PML_V2 and MOD16A2GF generated lower estimates. The Friedman test and Holm-adjusted Wilcoxon comparisons confirmed that these differences were systematic rather than the result of random interannual variability. The large Kendall's W further indicates that the relative ordering of the products remained highly consistent throughout 2001–2020. Comparable intercomparison studies have attributed such divergence to differences in forcing data, parameterization, model structure, vegetation representation, and treatment of surface-energy and soil-moisture processes [2,3,11,13,15,16].

Similar remote-sensing studies in West African basins have demonstrated that evapotranspiration patterns respond strongly to vegetation condition, climatic variability, land-cover modification, and crop-water stress, reinforcing the need to interpret ET estimates in relation to both product structure and environmental context [32].

The contrasting estimates are consistent with the different methodological foundations of the products. ERA5-Land and MERRA-2 are reanalysis-based datasets that simulate land–atmosphere exchanges using assimilated meteorological observations and physically based land-surface schemes [11,12]. GLDAS Noah relies on land-surface modelling driven by meteorological and satellite forcing [13]. MOD16A2GF applies a satellite-based Penman–Monteith framework, while PML_V2 explicitly couples carbon assimilation with vegetation transpiration, soil evaporation, and canopy interception [4,10]. TerraClimate uses a climatologically aided water-balance formulation [14]. These differences affect the representation of atmospheric demand, vegetation resistance, soil moisture, and available energy, leading to persistent offsets in ET magnitude.

Temporal behavior was more consistent than absolute ET magnitude. Only GLDAS Noah exhibited a statistically significant increasing trend after correction for serial autocorrelation, whereas the remaining products showed no significant long-term trends. This indicates that the principal disagreement among datasets concerned the amount of ET estimated rather than the direction of change through time. The result also demonstrates why autocorrelation testing was necessary: GLDAS was the only product with significant lag-1 dependence, and its trend therefore required confirmation using the Hamed–Rao modified Mann–Kendall test.

The significant increase detected in GLDAS should not be interpreted as independent evidence of a regional increase in actual evapotranspiration because the other five products did not show significant trends. Instead, it indicates that trend estimates remain sensitive to product-specific forcing and model behavior. Without long-term eddy-covariance or lysimeter observations, the present analysis evaluates inter-product consistency rather than absolute accuracy. Consequently, no dataset can be identified as universally superior from these results alone.

Overall, the findings demonstrate that product selection can materially affect estimates of atmospheric water loss across Hong Kong. Regional hydrological assessments should therefore avoid treating the six datasets as interchangeable and should report multi-product spread or uncertainty alongside any selected ET estimate [2,3,15].

4.2. Spatial Uncertainty and the Influence of Land Cover

The coefficient of variation analysis demonstrated that substantial disagreement exists among the six evapotranspiration products throughout Hong Kong. Although the spatial

distribution of uncertainty varied locally, mean CV values remained consistently high across all major land-cover classes, ranging from 28.33% over permanent water bodies to 29.12% over built-up areas. The relatively narrow range of CV values indicates that inter-product uncertainty was remarkably consistent despite differences in vegetation cover, surface moisture, and land use.

The consistently high uncertainty suggests that differences among the products are primarily associated with variations in model formulation rather than land-cover characteristics alone. Each dataset estimates evapotranspiration using different combinations of meteorological forcing, vegetation parameterization, soil-moisture representation, and energy-balance calculations. Consequently, even when products are evaluated over the same landscape, structural differences in model design can produce systematic divergence in estimated ET [2–4,10,15]. Similar conclusions have been reported in previous multi-product intercomparison studies, which found that algorithmic differences often contribute more to uncertainty than environmental variability itself [15–18].

Built-up areas and grassland exhibited the highest mean CV values, although these classes occupied relatively small proportions of the study area. Tree cover, which represented the largest land-cover class, also showed high uncertainty, indicating that disagreement among products was not confined to urban environments or sparsely vegetated landscapes. Permanent water bodies produced the lowest mean CV, but the difference from the remaining classes was small, suggesting that no land-cover type consistently improved agreement among the evaluated products.

The spatial uncertainty map further illustrates the influence of Hong Kong's heterogeneous landscape. Forests, urban areas, reservoirs, coastal wetlands, and mountainous terrain occur within relatively short distances, creating complex transitions between land-cover types. Such heterogeneity increases the likelihood of mixed-pixel effects, particularly for coarse-resolution products such as GLDAS Noah and MERRA-2, where a single grid cell may represent multiple land-cover types simultaneously. Although all datasets were harmonized to a common 500 m grid for comparison, resampling cannot recover the spatial information absent from the original coarse-resolution products. Consequently, part of the observed disagreement reflects differences in the effective spatial support of the datasets rather than differences in evapotranspiration alone.

These findings highlight the importance of incorporating uncertainty assessment into regional evapotranspiration studies. Reporting only a single ET product may underestimate the range of plausible evapotranspiration values, particularly in environmentally heterogeneous regions. Multi-product comparisons, together with quantitative uncertainty measures such as the coefficient of variation, provide a more transparent basis for hydrological assessment and enable users to identify areas where confidence in ET estimates is relatively high or low. Consequently, uncertainty information should accompany ET products when they are used to support water-resource management, ecosystem monitoring, or environmental decision-making [2,3,15,18,19].

4.3. Implications for Wetland Evapotranspiration Assessment

The Mai Po Marshes analysis demonstrates the importance of considering spatial scale when applying global evapotranspiration products to coastal wetlands. Although the six products produced substantially different annual ET magnitudes, they showed only negligible differences among mudflat or bare wetland, open water, and wetland vegetation after harmonization to the common analysis grid. The small within-product variation indicates that the products represent the wetland primarily as a regional hydrological unit rather than resolving evapotranspiration differences among individual habitat types.

This behavior is largely explained by differences between the size of the wetland and the native spatial resolution of the ET products. While MOD16A2GF and PML_V2 provide 500 m observations, ERA5-Land, GLDAS Noah, TerraClimate, and particularly MERRA-2 operate at much coarser native resolutions. Resampling these datasets to a common 500 m grid improves spatial alignment but does not increase their intrinsic spatial information. Consequently, multiple habitat types within Mai Po may be represented by a single coarse native pixel, reducing the ability of the products to capture fine-scale ecological variability. Similar limitations have been reported in previous evaluations of global ET products over fragmented landscapes and coastal ecosystems, where mixed-pixel effects become increasingly important as landscape heterogeneity increases [2,3,10,15].

Despite these limitations, the evaluated products remain valuable for regional wetland applications. Their long temporal records, complete spatial coverage, and consistent processing make them suitable for monitoring long-term changes in regional evapotranspiration, assessing climatic variability, and supporting large-scale hydrological studies. However, investigations requiring habitat-scale ET estimates, ecological process analysis, or wetland restoration planning should integrate higher-resolution satellite observations, field measurements, or locally calibrated surface energy-balance models to better represent the spatial complexity of coastal wetlands [4,7,10,21].

Overall, the Mai Po assessment demonstrates that the suitability of global ET products depends strongly on the spatial scale of the intended application. They provide regional-scale ET estimates suitable for broad hydrological interpretation.

4.4. Implications for Hydrological Applications and Product Selection

The results of this study have important implications for the application of global evapotranspiration products in hydrological and environmental studies. The statistically significant differences observed among the six datasets indicate that product selection can substantially influence estimates of atmospheric water loss and, consequently, calculations of water balance, drought severity, irrigation demand, groundwater recharge, and ecosystem water use. Because no product consistently agreed with all others, the use of a single ET dataset may introduce systematic bias into regional assessments [2,3,15].

More broadly, hydro-climatic risk assessments have shown that climatic stress can propagate spatially across connected ecosystems, emphasising the value of integrating ET uncertainty with wider ecosystem-risk and water-resource analyses [33,34].

The analyses also demonstrate that different products are suited to different applications. ERA5-Land and TerraClimate provide relatively stable long-term estimates suitable for regional climate and hydrological analyses, whereas MOD16A2GF and PML_V2 offer greater spatial detail for landscape-scale studies. GLDAS Noah was the only dataset exhibiting a significant long-term increase in ET, while MERRA-2 showed comparatively large interannual variability. These differences reflect the influence of contrasting model formulations and forcing datasets rather than differences in the underlying environmental conditions.

The incorporation of uncertainty analysis represents an important contribution of this study. Rather than relying on a single product, the combination of multi-product comparison, formal statistical testing, and spatial uncertainty assessment provides a more comprehensive evaluation of evapotranspiration than is typically presented in regional studies. Reporting uncertainty alongside ET estimates enables users to better understand the confidence associated with model outputs and supports more informed interpretation of hydrological analyses.

Overall, the proposed evaluation framework is transferable to other coastal regions where multiple global ET products are available but independent validation data are limited.

By integrating complementary datasets, robust statistical analyses, and explicit uncertainty assessment, the framework provides a practical approach for selecting evapotranspiration products according to study objectives and spatial scale while improving the transparency and reliability of regional hydrological assessments.

4.5. Study Limitations and Future Research

This study has several limitations. First, the ET products were compared with one another because continuous eddy-covariance, lysimeter or other ground-based ET observations covering Hong Kong and the Mai Po Marshes were unavailable. The results therefore quantify inter-product consistency and structural uncertainty rather than absolute accuracy. Second, resampling coarse products to a common 500 m grid improved spatial alignment but did not increase their effective spatial information. The Mai Po results should consequently be interpreted as regional-scale ET estimates rather than habitat-scale measurements. Third, the analysis did not formally attribute temporal ET variation to rainfall, temperature, vegetation change or urban expansion. Although product algorithms and forcing data provide plausible explanations for the observed differences, causal attribution requires additional climate, land-cover-change and field-observation datasets. Future research should establish an eddy-covariance monitoring site in the Mai Po wetland, evaluate downscaling and data-fusion methods, and extend the framework to other wetlands along the East Asian–Australasian Flyway.

5. Conclusions

This study presented a comprehensive evaluation of six widely used global evapotranspiration (ET) products across Hong Kong and assessed their applicability for regional hydrological analysis and wetland-scale monitoring using the Mai Po Marshes as a representative coastal wetland. By integrating long-term satellite and reanalysis datasets with statistical comparison, trend analysis, and spatial uncertainty assessment, the study provides an improved understanding of the consistency and limitations of contemporary global ET products in a heterogeneous coastal environment.

The six products exhibited similar broad spatial patterns but differed significantly in annual ET magnitude. ERA5-Land consistently produced the highest ET estimates, whereas GLDAS generated the lowest values. The Friedman repeated-measures test and Holm-adjusted Wilcoxon comparisons confirmed that these differences were statistically significant, demonstrating that the products should not be considered interchangeable. Among the evaluated datasets, only GLDAS exhibited a statistically significant increasing trend after accounting for serial autocorrelation, while the remaining products showed no significant long-term trends.

Spatial uncertainty analysis revealed consistently high disagreement among the six products across all major land-cover classes. Mean coefficients of variation differed only slightly among built-up areas, forests, mangroves, grassland, and permanent water bodies, indicating that uncertainty was primarily associated with differences in model structure, forcing datasets, and algorithm design rather than land-cover characteristics alone. These findings emphasize the importance of reporting uncertainty together with ET estimates when global datasets are applied to regional hydrological studies.

The Mai Po case study demonstrated that the evaluated products can provide regional-scale estimates of atmospheric water loss over the wetland but cannot reliably distinguish ET among individual habitat types after spatial harmonization. Consequently, these datasets are appropriate for regional hydrological monitoring and long-term environmental assessment but should be applied cautiously for habitat-scale ecological investigations.

Overall, this study demonstrates that multi-product evaluation combined with rigorous statistical testing and uncertainty analysis provides a more reliable basis for regional evapotranspiration assessment than reliance on any single global dataset. The proposed framework offers a practical approach for selecting appropriate ET products according to study objectives and spatial scale and can be readily applied to other coastal and urban environments. Future research should integrate global ET products with higher-resolution satellite observations and field measurements to improve evapotranspiration estimation in heterogeneous landscapes and support more effective water-resource management and wetland conservation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18151897/s1>, Table S1: Holm-adjusted pairwise Wilcoxon signed-rank comparisons of annual evapotranspiration estimates from the six products across Hong Kong during 2001–2020.

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Data Availability Statement: All datasets are openly available via Google Earth Engine: ERA5-Land, GLDAS, TerraClimate, PML_V2, MOD16A2GF and MERRA-2 evapotranspiration products, and Sentinel-2 surface reflectance (COPERNICUS/S2_SR_HARMONIZED) for the Mai Po land-cover classification (2001–2020). The Google Earth Engine and Python processing scripts are available from the corresponding author upon reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

ET	Evapotranspiration
GEE	Google Earth Engine
CV	Coefficient of Variation

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