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Quantifying evapotranspiration in Nepal using multiple constraints

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Highlights:

- The Budyko framework detected water imbalance issues in hydrometeorological monitoring data for large watersheds
- Existing remote sensing products overestimated evapotranspiration (ET) for high and low elevations
- Integrated ecohydrological modeling reduced ET estimate errors and uncertainty in Nepal

Abstract

Evapotranspiration (ET) research is rare but is essential for understanding the impacts of climate change and forest management on water resource in Nepal. This study assessed eight global remote sensing-based ET products including GLASS, GLEAM, PMLv2, REA, PEW, ETmonitor, SSEBop and SEBAL, and an ecohydrolgical model, WaSSI using locally constructed 12 watershed-scale water balance datasets. Additionally, the Budyko framework was employed to constrain ET estimates. We found serious water imbalance issues in the hydrometeorological records for medium-sized basins where measured streamflow exceeded precipitation (P) and ET/P values substantively deviated from the theoretical Budyko curve. The accuracy of the remote sensing ET products varies at selected watersheds with large elevation gradients. We found considerable modeling errors with ET overestimated, especially in high elevations among these remote sensing products. Nationally, the eight remote sensing models do not agree on the temporal trends for annual ET over the past two decades. We identified potential causes to the large errors of the ET products: 1) meteorological input data used to drive the potential ET model and ET model, 2) model algorithms causing overestimates of ET at high elevations, and 3) underestimation of precipitation and overestimation of leaf area index at high elevations. We estimated mean annual ET for High Himalya, High Mountain, Middle Mountain, Low Mountain, Terai Plain as 257 mm, 544 mm, 764 mm, 844 mm and 892 mm, respectively. This study underscores the importance of ground measuring and integrated modeling of water balances in constraining remotely estimated ET in the Himalya region.

Keywords: Hydrology, Modeling, Remote sensing, Water Balances

Plain Language

This study aims to improve understanding the water balance across Nepal, a ‘water rich’ region representing Asia’s ‘Water Tower’ on the Himalaya mountains and a

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biodiversity 'hotspot' in the world. Most of the region is 'greening up' due to climate change and forest management, and some areas are becoming urbanized due to demographic shifts during the past two decades. Understanding evapotranspiration (ET), a key variable of the water and carbon cycles, is extremely important to predict the likely environmental impacts of climate and land use change in the region. We examined the accuracy of the eight global ET products and a ecohydrological model in estimating ET using hydrometeorological data collected from 12 local watersheds and the theoretical framework. Our study identified potential issues of monitoring data and the remote sensing products for hydrological research and applications. Through careful cross-check of the fidelity of the ET products with alterative modeling results and literature ET data, we provided recommendations to improve the quality of the global ET products especially for high elevation watersheds where ET estimates are most problematic. Information from this study is helpful to reasonably use the widely available global ET data for water resource management and guide ecohydrological research in this 'data scarce' region in Asia.

1. Introduction

The Himalayan Mountain chains and the adjacent Tibetan Plateau represent Asia's 'Water Tower' that sustain several large rivers and providing water to more than a billion people in the surrounding lowlands (Zeng et al., 2017; Zheng et al., 2021; Leng et al., 2023; Immerzeel et al., 2010). The Trans-Himalayan region is warming rapidly (Dimri et al., 2018), and according to observational reports, the average temperature in

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the Himalayan region of Nepal has been increasing at a rate of 0.6 °C/decade from 1977 to 2002 (Shrestha & Aryal 2011). The ecological, climatic, and hydrological responses to climate change have become a focal point of research in the recent decades (Kansakar et al., 2004; Paudel et al., 2023; Kattel et al 2022; Leng et al., 2023). In particular, little is known about the hydrology in the middle mountains (also known as Lesser Himalaya) (Khanal & Watanabe, 2017; Bruijnzeel et al., 2024) where forests and croplands dominate the landscape that support livelihood of the local communities including critical spring water supply. However, such water resources are especially vulnerable to climate and land-use and land-cover changes in the monsoon climate (Aryal et al., 2014; Bruijnzeel et al., 2024).

Evapotranspiration (ET) is a critical component of the water cycles and is closely coupled with energy and carbon fluxes, and biodiversity, especially in humid forested areas (Sun et al., 2011a,b; Yi et al., 2024). ET rates are rising in many parts of the world including Nepal due to various reasons, ranging from global warming to local land-cover and land-use changes (Jung et al., 2010; Mu et al., 2011; Dong and Dai, 2016; Li et al., 2020). Accurately quantifying ET viability is essential for climate mitigation and adaptation through forest management (Trambauer et al 2014; Sun et al., 2024; Duarte et al., 2024). Understanding the fundamental drivers of ET and hydrology in different regions is the first step towards developing effective water resource management strategies that must be tailored to local conditions (Teuling et al., 2009; Vinukollu et al., 2011a; Wei et al., 2025).

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Numerous methods are available to estimate ET at different scales (Sun et al., 2016) including eddy covariance (Swinbank 1951; Yi et al., 2024), soil water balance (Senay et al., 2011), sapflow + canopy/litter interception (Gong et al., 2007; Ghimire et al., 2014), lysimeters (Allen et al., 1989), surface energy balance (Bastiaanssen et al., 1998; Su 2002), mathematical modeling with various assumptions (Gan et al., 2021; Qiu et al., 1998, 2006, 2002; Mauder et al 2013; Fu 1996; Zhang et al., 2001). However, these methods are often costly and limited to small scales, uniform land surfaces, or long-term mean conditions (Liu et al., 2016; Xu et al., 2018).

Remote sensing technology emerged as an essential tool to scale up field station-based ET for hydrological modeling and water resources management at the regional or national scales (Yang et al., 2017; García-Santos, 2022; Yi et al., 20024). Many global remote sensing-based ET products are available that have been used in natural resource management such as crop yield prediction, irrigation water demand estimation, and drought risk assessment (Fisher et al., 2017; Lu et al 2021; Yao et al 2013, 2014; Fu et al., 2022; Martens et al., 2016; Miralles et al., 2011; Senay et al., 2013; Cheng et al., 2021; Laipelt et al., 2021; Zheng et al., 2022). A comparative study of 90 global ET products by Cai et al. (2024) found that while these products generally exhibit consistent spatial distribution on a global scale, significant differences exist in the magnitude and temporal trend in many cases. However, these global models have not been regularly evaluated in 'data poor' regions beyond where they were developed and parameterized and large errors may exist (Volk et al., 2024).

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Our recent ecohydrological studies in Nepal suggest that, amidst global warming, precipitation patterns and rainfall intensities have shifted (Luo et al., 2024), raising concerns in water stress due to drought and floods. In the meantime, the demands for water resources by growing urban populations and lowland agriculture are increasing (Lamichhane et al., 2019; Acharya et al., 2023; Singh et al., 2024). In this study, we consider that some of the observational data from Nepal also have considerable uncertainty. Additionally, various changes in land use and land cover caused by anthropogenic activities (e.g., Community Forestry, urbanization, road construction etc.) are perceived to have significant hydrological impacts in Nepal (Zhou et al., 2023; Gao et al., 2023). For example, there has been a debate about the effects of expanding pine forests on water yield and its contribution to the decline of spring water in Nepal (Bruijnzeel et al., 2024). Consequently, the region that is traditionally considered 'water rich' has shown a sign of water scarcity (Gurung et al., 2019). Unfortunately, studies on ecohydrology and land ET are extremely rare in Nepal (Ghimire et al., 2021; Badu et al., 2022; Bruijnzeel et al., 2025). Our previous ecohydrology studies in the region indicates large uncertainties in characterizing the environmental change (e.g., vegetation dynamics and ecosystem productivity) in the mountainous Nepal (Gao et al., 2023; Luo et al., 2024; Zhou et al., 2023).

This study aims to improve our understanding and quantification of the spatial and temporal patterns of ET in Nepal, under the pressures of data scarcity and observational data uncertainty. Given the lack of site-level direct field ET measurements, we

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employed global remote sensing ET products to accomplish our goals. These ET products were comprehensively assessed by measured water balance data at a few watershed locations and the Budyko framework and an ecohydrological model (WaSSI) across 385 watersheds across the country. Specifically, our objectives were to: (1) evaluate the quality of global ET products with multiple methods and data sources, and (2) examine the temporal and spatial distributions of ET along an elevation gradient at the monthly and long-term scale. We examine the discrepancies among the eight global ET products to understand processes that control regional ET. The multiple datasets and methods improved ET estimates with higher confidence and reduced uncertainty. Information from this study advanced our knowledge about the ecohydrology in the Lessor Himalya region.

2. Methods and Data Sources

2.1 Study Area

Nepal is a mountainous and landlocked country in South Asia bounded by an Indian foothill of the Himalaya to the south, east and west, and the Chinese Tibetan Plateau to the north (Fig. 1a). It covers a land area of 147,181 km^2 with extremely large altitudinal gradients ranging from about 60 m in the southeast to more than 8848 m (Mt. Everest) in the north. Along the elevation gradient, the country can be divided into five physiographical zones from the South to the North: The Terai in plains (< 750 m), Siwaliks (750 ~ 1500 m), Middle Mountains (1,500-3,000 m), High Mountains (3000 ~ 4000 m), High Himalaya (> 4000 m). The complex topography results in contrasting

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vertical climate zones, with a mean annual precipitation from 200 mm in some northern regions to more than 5000 mm in the south and a mean annual temperature ranging from -10 ˚C in the north to more than 30 ◦C in the south (Baniya et al., 2018; Koju et al., 2020; Zhou et al., 2023). The climate of Nepal can be categorized into four seasons: Pre-monsoon (March to May), Monsoon (June to September), Post-monsoon (October to November), and winter (December to February) (Kansakar et al., 2004). Winter represents the driest season, and Monsoon is the wettest season that receives over 80% of total annual precipitation (Kansakar et al., 2004).

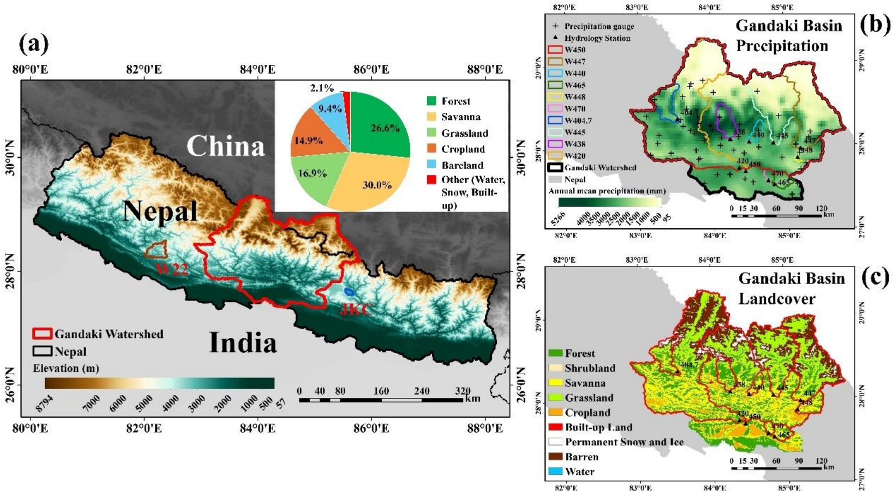

Figure 1. Watershed geographical locations and hydrometeorological stations in Nepal. **(a)** Elevation pattern and watershed boundary of the Gandaki Basin, Watershed 22, and the Jhikhu Khola Catchment (JKC) used for assessing evapotranspiration products. Insert is Nepal land cover summary derived from MCD12Q1 data © NASA LP DAAC and IGBP classification, **(b)** mean multi-year (1980-2020) precipitation (TPMFD gridded data © TPDC), location of selected watersheds and precipitation and hydrology measurement gauges in the Gandaki Basin, and **(c)** The land cover and land use (MCD12Q1 data, IGBP band) distribution in the Gandaki Basin.

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2.2 Hydrometeorological data and global remote-sensing based ET products

2.2.1. Watershed hydrometeorological monitoring for model validation

We assembled streamflow, precipitation, and potential ET data for 12 watersheds across central Nepal for assessing ET products and validating a hydrological model (Fig. 1a, 1b, 1c; Table 1). The Budyko framework was used to examine PET/P *vs* ET/P relationship to judge the overall quality of the monitored water balance data (Fig. 2). As presented later, only five watersheds were qualified for ET model validation purposes due to water imbalance issues found in the other seven watersheds.

Watershed actual ET (ET_{wb}) was calculated using water balance on the annual scale (Table 1). $ET_{wb} = P - Q - \Delta S$. Q is annual streamflow. At a multiple-year scale, change in annual soil storage (ΔS) was assumed to be negligible, but at annual it can be large.

2.2.2. **Remote sensing land surface data for estimating reference ET (ET_0) , potential ET (PET) and actual ET**

In addition to acquiring seven existing global remote sensing-based ET products, this study parameterized the surface energy balance SEBAL (Details in Supplemental Information) to enhance model comparisons (Table 1). High-resolution near-surface meteorological forcing dataset (e.g. air temperature, T_a, wind speed, w_s) for the Third Pole region (TPMFD,1979-2022) was used for running SEBAL (Zhou et al., 2021; Jiang et al., 2023). Land surface temperature (LST) products that consider the elevation effects were adopted (Zhang et al., 2019; Zhang et al., 2021; Zhou et al., 2017; Tang et al., 2024). MOD09A1 has a high spatial and temporal resolution for

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radiation. However, clouds result in large data gaps for monsoon season, and a method developed by Moody et al. (2005) was used to for gap-filling. The digital elevation model (DEM) data with a 90-m resolution was used to correct slope effects on net radiation and aerodynamic parameter (Allen et al., 2007). The TPMFD dataset was used to calculate the ET_0. Daily ET_0 rates were calculated using the Penman-Monteith FAO-56 method (Allen et al., 1994) for each pixel across Nepal for the period of 1980–2020. To maintain consistency of spatial resolution, all ET products were resampled to a 0.01° resolution when comparing their spatial variability along the elevation gradient. The TPMFD dataset was also used to calculate the PET. When running the WaSSI model, we estimated PET at the watershed scale within the framework of the WaSSI model, employing the Hamon algorithm (Hamon, 1961) for the calculation.

Table 1. Databases used for estimating watershed evapotranspiration by multiple methods

Data	Purpose	Resolution	Time Period	Reference
Precipitation	Water balance calculation and WaSSI model application	station site/daily	1980-2014	http://www.dhm.gov.np/
Runoff	Water balance calculation	station site/daily	1980-2015	http://www.dhm.gov.np/
DEM	SEBAL modeling	90 m	—	https://search.earthdata.nasa.gov
MOD09A1 (band 1 – 5 and band 7)	SEBAL modeling	500 m/8-day	2001-2022	https://lpdaac.usgs.gov

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MCD12Q1 (band 1, IGBP)	Missing value imputation on spatial scale in SEBAL	500m/1-year	2001-2022	https://lpdaac.usgs.gov
High-resolution near-surface meteorological forcing dataset for the Third Pole region (TPMFD)	SEBAL, WaSSI and P-M PET modeling	0.03°/daily	1979-2022	(Jiang et al., 2023) https://data.tpdc.ac.cn
Global Land Surface Satellite LAI (GLASS LAI)	WaSSI modeling	500m/8-day	2001-2020	http://www.glass.umd.edu/
A priori global 250m parameters for the SAC-SMA model	Soil parameters for WaSSI model input	250m	——	https://doi.org/10.25919/vj30-h988
European Space Agency's Global Land Cover gridded maps	WaSSI modeling	300m	1992-2022	https://cds.climate.copernicus.eu/
Thermal and Reanalysis Integrating Moderate - resolution Spatial - seamless LST – Tibetan Plateau (TRIMS LST-TP)	SEBAL modeling	1 km/daily	2000-2021	(Zhang et al., 2021) https://data.tpdc.ac.cn
Global Land Surface Satellite ET (GLASS)	ET Products Comparison	0.05°/8-day	1982-2018	(Yao et al., 2014) http://www.glass.umd.edu/
Global Land Evaporation Amsterdam Model (GLEAM)	ET Products Comparison	0.25°/monthly	1980-2022	(Miralles et al., 2011) https://www.gleam.eu/
ETMonitor Global Actual Evapotranspiration Dataset (ETMonitor)	ET Products Comparison	0.01°/monthly	2001-2018	(Zheng et al., 2022) https://data.tpdc.ac.cn
Proportionality hypothesis-based surface Energy-Water Balance model (PEW)	ET Products Comparison	0.1°/monthly	1982-2018	(Fu et al., 2022) https://data.tpdc.ac.cn
Penman-Monteith-Leuning Version 2 (PMLv2)	ET Products Comparison	0.01°/8-day	2001-2020	(Zhang et al., 2019) https://earthengine.google.org
Reliability Ensemble Averaging (REA)	ET Products Comparison	0.25°/monthly	1990-2017	(Lu et al., 2021) https://data.tpdc.ac.cn
Surface Energy Balance Algorithm for Land (SEBAL)	ET Products Comparison	0.01°/8-day	2001-2020	(Bastiaanssen et al., 1998)

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Operational Simplified Surface Energy Balance model parameterized (SSEBop)	ET Products Comparison	0.01°/monthly	2003-2021	(Senay et al., 2013) https://earlywarning.usgs.gov/
Operational Simplified Surface Energy Balance model parameterized Version 6 (SSEBop V6)	ET Products Comparison	0.01°/monthly	2013-2023	(Senay et al., 2023) https://earlywarning.usgs.gov/
Water Supply Stress Index (WaSSI) model	ET Products Comparison	385 watersheds	2000-2020	Sun et al. (2011)

2.3 Descriptions of the global remote sensing ET products and the WaSSI model

We compared simulations of the SEBAL model parametrized by this study and other seven existing global ET products (Table 2). These ET models were briefly described below to highlight the unique features of the different modeling approaches (Table 2). We assessed model accuracy using mean annual ET estimated by the water balance methods for five selected watersheds that have sufficient data quality as judged by the Budyko framework. In addition, an integrated ecohydrological model (WaSSI) was parameterized to simulate water balance across 385 watersheds to provide further assessment of the accuracy of the global ET products when used in Nepal.

Table 2. A comparison of key required input variables for eight remote sensing-based ET models and the WaSSI ecohydrological model

Model	Temperature (LST or T_a)	Precipitation	Vegetation Index	Topography	Soils	Dynamic model	Assembled multiple ET products
SEBAL	✓		✓	✓	✓		
GLASS							✓
GLEAM	✓					✓	
ETMonitor	✓		✓			✓	

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PEW	✓	✓	✓			✓	
PMLv2	✓		✓			✓	
REA							✓
SSEBop	✓		✓	✓		✓	
WaSSI	✓	✓	✓	✓	✓	✓	

2.3.1 Land Surface Energy Balance Model (SEBAL)

The widely used SEBAL model is developed from a simplified land surface energy balance principle (Net radiation = Latent heat (LE) + Sensible Heat (H) + change in heat storage) (Bastiaanssen et al., 1998a). The SEBAL model requires two crucial points representing the ‘hot’ and ‘cold’ pixels over a study area to model sensible heat (H). Based on normalized difference vegetation index (NDVI), LST and land cover data, the cold pixel was selected in areas with well-vegetated pixels (with NDVI > 0.7) and the hot pixel was selected in areas with low-vegetated (with NDVI < 0.3) (Laipelt et al., 2021). Estimating H involves various air and surface characteristic parameters for aerodynamic process. LE is estimated as the difference between net radiation and sum of H and change in heat storage. Therefore, in addition to meteorological variables, ground vegetation cover data are also considered to characterize net radiation.

The LE or ET represents an instantaneous flux. To estimate daily or longer period ET (denoted as ET_d), the instantaneous LE or ET must be temporally scaled up to cover 24 hours or more. A linear interpolation method is used in the SEBAL to interpolate ET from 8-day scale to obtain ET in daily scale (Yang et al., 2012). SEBAL has been applied and evaluated in both arid (Almhab et al., 2008; Adem et al., 2023) and humid

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regions (Jin & Hao, 2020; Jin et al., 2023; Sun Z. et al., 2011) (see Supplementary for details of SEBAL model descriptions).

2.3.2 Global Land Surface Satellite (GLASS)

The GLASS product is considered as a combination of different LE products through Bayesian methods (Yao et al., 2014). The accuracy of GLASS product has been evaluated only at the global scale. Yao et al. (2013) first used the modified Priestley-Taylor (P-T) model to calculate the latent heat flux corresponding to different ET components (such as canopy evaporation, vegetation transpiration, soil evaporation, and wet soil surface evaporation). The sum of the latent heat fluxes for these different components represents the actual total latent heat flux for ET. Yao et al., (2014) then merged this data with other global latent heat flux data products (such as MODIS LE (MOD16), revised remote-sensing-based Penman-Monteith LE (RRS-PM), Priestley-Taylor LE algorithm from Jet Propulsion Laboratory (PT-JPL), and Semiempirical Penman LE algorithm from the University of Maryland (UMD-SEMI) using Bayesian methods to obtain the final GLASS product. Users can apply a conversion coefficient to transform latent heat flux into actual ET.

2.3.3 Global Land surface Evaporation: the Amsterdam Methodology (GLEAM)

The GLEAM derives ET in two steps: first, the P-T model is used to estimate PET; second, the PET is corrected to become ET based a range of soil moisture stress factors (Miralles et al., 2011; Martens et al., 2017). This product has two prominent features: 1) the influence of the soil water stress on ET was considered using a soil water balance model, and 2) microwave data was induced to account for the effects of soil properties. GLEAM places more emphasis on the impact of soil-related moisture information on evapotranspiration estimations, such as soil water content, soil water budget, and root-zone water balance. The GLEAM product has also been validated and applied in China and other countries or regions (Yang et al., 2017; Liu et al., 2021; Khan et al., 2020).

2.3.4 ETMonitor Global Actual Evapotranspiration Dataset (ETMonitor)

ETMonitor is a distributed ET model that integrates land surface characteristics (Zheng et al., 2022). The model considers evaporation, transpiration, or sublimation from soil, vegetation, water bodies, and snow within the same pixel. The model considers three parts of the energy balance, the radiation processes of vegetation and soil, the ecophysiological processes of vegetation, and the water balance processes (vegetation interception, transpiration, soil evaporation and infiltration processes, water body evaporation, and snow sublimation). On the global scale, two parameters $r_{s,min}$ (minimal stomatal resistance for plant transpiration) and K_D(the vapor pressure deficit (VPD) stress parameter for plant transpiration) are estimated using the eddy flux observations over 236 sites. However, there has been limited validation of the product at a regional scale.

2.3.5 Proportionality hypothesis-based surface Energy-Water balance model (PEW)

PEW (Fu et al., 2022) is built based the generalized proportionality hypothesis on water balance (Poncea and Shetty, 1995). The proportionality hypothesis, based on the Soil

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Conservation Service (SCS) curve number method, assumes that the ratio of actual continuing abstraction to its potential value is equal to the ratio of direct runoff to its potential value. In this method, soil evaporation and vegetation intercepted evaporation are the two key parameters for partitioning precipitation. These two parameters can be used to estimate ET based on the Priestley Taylor-Jet Propulsion Laboratory (PT-JPL) formulations (Fisher et al., 2008). The PEW product incorporates precipitation data in its model construction, which is one of its unique features compared to other remote sensing evapotranspiration products (Table 2). The PEW product is a global ET product that has emerged in recent years and has not yet been widely used.

2.3.6 Penman-Monteith-Leuning Model (PMLv2)

PMLv2 (Zhang et al., 2019) is an updated version of the PMLv1 model (Zhang et al., 2016). Leuning surface conductance model (Leuning et al., 2008) together with Penman-Monteith equation are used to estimate plan transpiration (E_t) in PMLv1. In PMLv2, a water-carbon coupled canopy conductance model is introduced to estimate E_t. The model for calculating soil evaporation (E_s) and evaporation of precipitation intercepted by the vegetation (E_i) remains the same as PMLv1. PMLv2 is also further improved by incorporating the meteorological features constraint to E_t. This product has a higher spatial resolution than other products. The PMLv2 product has undergone model calibration and cross-validation at 95 flux sites across twelve different land cover types globally. These validation sites are primarily concentrated in North America, Europe, and Australia (Zhang et al., 2019).

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2.3.7 A Harmonized Global Land Evaporation Dataset with Reliability Ensemble Averaging Method (REA)

REA ensembled products are constructed through merging four ET modeling products (Giorgi and Mearns, 2002). REA extracts the most reliable information from each product by minimizing the impact of "outliers" or underperforming models. Subsequently, REA method can reduce the uncertainty and stands out in terms of computational efficiency. In this product, the fifth-generation ECMWF Reanalysis (ERA5) ET, the Second Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) ET, GLEAM ET and Global Land Data Assimilation System ET are merged to a single data set that represents a long-term (1980–2017) daily ET product at a spatial resolution of 0.25° (Lu et al., 2021).

2.3.8 Operational Simplified Surface Energy Balance (SSEBop)

The SSEBop ET product is also based a surface energy balance method (Senay et al., 2013). However, compared to SEBAL, this method does not involve complex aerodynamic processes, making the computation relatively simple (Chen et al., 2016). It also takes into account of the influences of vegetation surface on ET to a certain extent. This consideration is reflected by two key parameters, difference between hot and cold boundary conditions (dT) and wet-bulb (cold boundary condition (T_c) for estimating ET. Temperature and PET are key variables for calibrating and constructing model. The SSEBop product has developed multiple versions, with the latest being SSEBop V6. This version mainly updates the model parameters, PET data and Remote

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sensing data (VIIRS for V6, MODIS for previous version). Given that this version has a shorter usable lifespan, it is difficult to match the time periods for watershed comparison analyses and trend analyses with other products, so we still use the versions prior to SSEBop V6 for these comparisons. However, in the analyses of product performance at different elevation characteristics and seasonal characteristics across different products, we included the SSEBop V6 dataset. The SSEBop product has also undergone comparative validation in countries such as Brazil (Dias et al., 2019), China (Yin et al., 2020), America (Chen et al., 2016) and regions in Africa (Weerasinghe et al., 2020).

2.3.9 Water Supply Stress Index Model (WaSSI)

We adopted a watershed scale ecohydrological model, WaSSI, to provide one more independent benchmark ET dataset to further evaluate remote sensing-based ET products. Our hypothesized that the WaSSI model that integrates climate, vegetation, and soil reflects more of the reality of watershed hydrological processes in comparing to remote sensing ET techniques, thus the ET estimates by WaSSI are more constrained and more accurate at the watershed to regional scale.

The WaSSI model is a monthly-scale water and carbon balance model designed for regions with limited driving variables and data (Sun et al., 2011). The model has been successfully applied in the U.S. (Caldwell et al., 2012; Li et al., 2020; Liu et al., 2021), China (Liu et al., 2013; Chen et al., 2024), Australia (Liu et al., 2018), Rwanda (Bagstad et al., 2018), and recently in Germany to quantify the impacts of land use change

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including forest management (e.g. thinning) (Sun et al., 2015), urbanization (Li et al., 2021; Chen et al., 2024) and climate variability (Duan et al., 2017) on ET and water yield. The core of the WaSSI model is the empirical ET sub-model that simulates ecosystem ET as a function of monthly precipitation, potential ET, and leaf area index (Sun et al., 2011). Monthly ET is further constrained by soil water availability during dry periods. Soil moisture dynamics and subsurface flow processes are simulated with a deterministic and conceptual lumped-parameter bucket-type soil hydrology model. The snowmelt and snowpack processes are accounted as a function of mean monthly air temperature. Details of the model algorithms and flow chart are found in Sun et al. (2011) and Liu et al. (2013), respectively. In this study, we delineated 385 watersheds across Nepal and its surrounding areas as the basic modeling domain (Fig. S2). Consequently, WaSSI model simulation outputs include monthly PET, ET, and water yield for each of the 385 watersheds.

2.5 Assessing Accuracy of ET estimates

2.5.1. The Budyko framework for assessing hydrological data quality and ET estimates with remote sensing and modeling

The Budyko (1974) framework has been widely used to how precipitation (P) partitions into ET and runoff, providing the long-term average water and energy balance at a broad scale (Sposito, 2017). Budyko’s conceptual models indicate precipitation partitioning is controlled by both radiant energy (represented by PET) and water availability and land surface characteristics (Gerrits et al., 2009; Zhang et al., 2001).

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Thus, the Budyko models provides a convenience reference for long-term mean water and energy balance for a watershed or region. Any large deviations from the general Budyko model curves may indicate data issues. Thus, the Budyko framework can be used as a first order criteria to judge if estimated ET from models or ET using the water balance method (ET_{WB}) rates are reasonable.

In this study, we used the Fu model (Fu, 1981; Fu, 1996) to represent watersheds with mixed land uses and the parameter w was set as 2.5 as suggested by Zhang et al. (2004) who derived the parameter using global ET data:

$$\frac{ET}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P}\right)^{w}\right]^{1/w} \quad (1)$$

This model indicates that ET/P and ET/PET always are less than 1.0 and increases with PET/P nonlinearly, depending the value of land surface parameter, *w*.

2.5.2. Statistical criteria for assessing ET estimates with watershed balance data

The quality of the eight different ET products and WaSSI model was assessed using ET estimates relative to ET derived by the water balance (ETwb) method. Following variables were used at pixel (remote sensing products) or watershed (WaSSI model) levels: mean bias error (MBE), mean relative error (MRE), root mean squared error (RMSE).

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(ET_{sim} - ET_{wb}) \quad (2)$$

$$MRE = MBE/Mean\ ET_{wb} \quad (3)$$

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$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ET_{sim} - Mean\ ET_{wb})^2} \quad (4)$$

Where, ET_{sim} represents the simulated ET by various ET products or the WaSSI model. The *n* corresponds to the number of annual observations.

2.6 ET Trend analysis

We estimated the long-term annual ET trend from 2001 to 2017 for each of the products on a per-pixel basis by the non-parametric Mann-Kendell method (Mann, 1945; Kendall, 1975). The methods are recommended by the World Meteorological Organization and are widely used in meteorological research (Liu et al., 2010; Darshana et al., 2013). The core of this method is the estimation of the standardized test statistic Z:

$$Z = \begin{cases} \frac{s-1}{\sqrt{Var(s)}} & if\ \ s > 0 \\ 0 & if\ \ s = 0 \\ \frac{s+1}{\sqrt{Var(s)}} & if\ \ s < 0 \end{cases} \quad (5)$$

In this equation, Var represents the variance, parameter S can be calculated as below:

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sgn(X_j - X_k) \quad (6)$$

X_j and X_k represent the value of the j-th and k-th ET data point in the time series, and n is the total number of sample data points.

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3 Results

3.1 Observation Data Quality Evaluation

In the verification of the original observation data, this study adopted the reference ET formula recommended by the Food and Agriculture Organization (FAO) as the standard. Based on the Budyko framework, we identified serious water imbalance issues for watershed W404.7, W440, W445, W447, W448 (Fig. 1). For example, mean measured runoff in W404.7 and W445 exceeded precipitation (See support information Fig. S1), resulting in negative ET_{wb} in these two watersheds. Similarly, we found, W448, W465 had large deviations from the Budyko framework mostly for the early periods (1980s), indicating data quality issues as well. Although long-term watershed balances for W447 and W440 were reasonable as determined by the Budyko framework (Fig. 2), reported streamflow exceeded precipitation in certain years (Fig. S1). For W470, the relationship between precipitation and runoff aligns with the Budyko curve (Fig. 2). However, the precipitation data used for this W470 were derived from kriging interpolation from surrounding precipitation stations and might involve errors. Consequently, we removed these watersheds with water balance issues for further assessment analysis about the accuracy of the ET products. Only five watersheds: W420, W438, W450, W22, JKC were retained (Figure 3).

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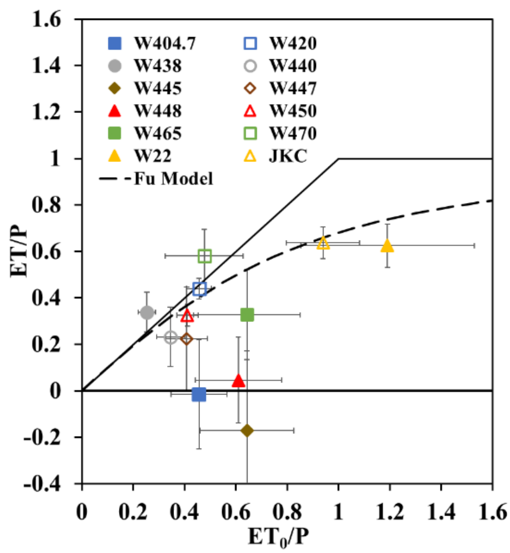

Figure 2. The patterns of average ET_0/P and ET/P in different sub-basins of the Gandaki River Basin during different periods on the Budyko framework (Fu, 1996). Mean ET is estimated as the differences between annual precipitation and streamflow. The error bars are standard deviation (STD).

3.2 Model assessment with data from five watersheds

Overall, WaSSI, SEBAL, GLASS, PMLv2, and REA products have relatively smaller errors (<5.3%), while the deviations of the PEW, ETMonitor, GLEAM, and SSEBop products exceeded 10% (Table 3). However, the performance of these eight products and WaSSI varies across different watersheds.

For large-scale watersheds (W420, W450) (watershed area = 11778, 31732 km^2 respectively), GLASS, PMLv2, REA, and SEBAL perform well. In W420, all eight ET products show underestimates for this watershed (Fig. 3b). Among these four products, SEBAL performs the best, with an MRE of -10.2%, MBE of -92 mm, and RMSE of 124 mm. In W450 (a large basin), GLASS, PMLv2, REA, and SEBAL all perform well,

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with absolute MRE values below 8%. PMLv2 performs best, with an MRE of -1.1%, MBE of -8 mm, and RMSE of 93 mm. Notably, WaSSI shows a satisfactory result with an MBE of -83 mm and MRE of -11%.

For the medium-sized watersheds (W438, W22) (watershed area is 829 and 813 km^2 respectively), all ET products show significant errors. Notably, for W438, the average MRE for all products is -39.8%, with an MBE of 513 mm, and RMSE of 653 mm indicating a clear discrepancy between the ET products and water balance results. However, it is worth noting that the ET_{wb}/P exceeds the energy limit of the Budyko framework ($ET>ET_0$). This watershed has a large ET_{wb} (about 1300 mm) and most models show underestimate (Fig 3b).

For the W22 watershed (watershed area = 813 km^2), GLASS, SEBAL, and PMLv2 ET/P deviate from the Budyko framework (Fig. 3a), and most products show an overestimate of ET/P and ET when compared to ETwb (Fig. 3b). Lastly, for the small watershed (JKC) (watershed area= 323 km^2), WaSSI modeled ET and ETMonitor product show the smallest difference from the water balance result (Fig. 3b), with the lowest MRE of 2.6% (WaSSI) and 4.2% (ETMonitor), MBE of 19 mm (WaSSI) and 31 mm (ETMonitor). RMSE of WaSSI and ETMonitor is 57 mm and 67 mm, respectively.

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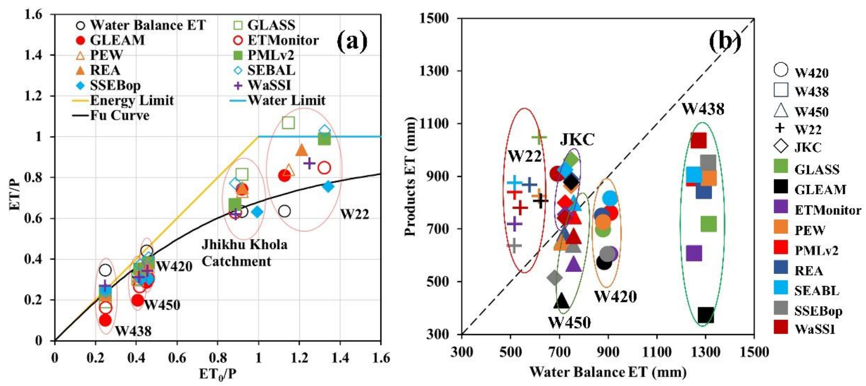

Figure 3. (a) Assessing global ET products for five watersheds using the Budyko framework by comparing the theorical Fu model (Zhang et al., 2004) and estimated ET/P-ET$_0$/P relationship by the watershed water balance method and nine models. **(b)** Comparison between ET_{WB} and modeling ET for validation sub-watersheds. Unique symbols present five different watersheds color coded with ET model name.

Table 3. A summary of statistics of estimate bias by eight remote sensing products and the WaSSI model for five selected watersheds. The time period for ET_{WB} (Precipitation, P – Streamflow, Q) in Jhikhu Khola Catchment (JKC) is 1993-2005 and other watersheds is 1980-2014.

Models	Mean±Std (mm/year)	Mean Bias Error (mm/year)	Mean Relative Error (MRE)	Root mean squared error (RMSE) (mm/year)
ETwb	949±224	-	-	-
SEBAL	832±244	-36	5.1 %	357
GLASS	854±245	-23	5.3 %	252
PMLv2	833±244	36	2.9 %	304
REA	843±244	-61	-1.7 %	271
PEW	853±245	-181	-13.4 %	320
ETMonitor	833±244	-239	-19.6 %	418
GLEAM	853±239	15	10.5 %	267
SSEBop	833±269	-162	-15.2 %	291
WaSSI	785±131	-56	-1.3%	227

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3.3 A comparison of modeled spatial and temporal patterns of mean ET

At the monthly scale, most products show that ET rates began to rise rapidly around March, peaked in July-August corresponding to the Monsoon season, and sharply declined in October (Fig. 4). In contrast, WaSSI ET did not rise appreciably till middle April (Fig 4j), much later than the remote sensing products. In areas below the 3,000 m altitude, monthly peak ET rates were generally over 60 mm (Fig.4). Again, significant discrepancies in ET values among different products were found mostly in high elevations. Notably, peak monthly ET values by GLEAM and SSEBop were much lower than other products at elevations higher than >3000 m. Overall, SEBAL an WaSSI gave higher monthly ET values (>110 mm) that were predominantly concentrated between June and September, overlapping the high rainfall and peak growing season.

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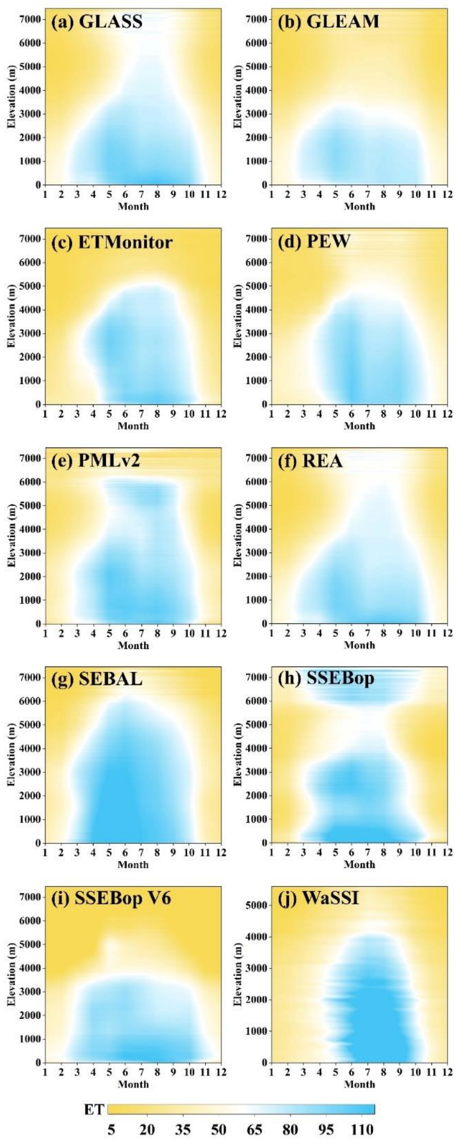

Figure 4. Comparison of simulated ET characteristics at different elevations on a monthly scale. (a) GLASS, (b) GLEAM, (c) ETMonitor, (d) PEW, (e) PMLv2, (f) REA, (g) SEBAL, (h) SSEBop, and (i) SSEBop V6, and (j)WaSSI.

Overall, as expected, modeled ET rates decrease with the rise of elevation. However, relatively larger discrepancies present below the 2000 m elevation line. In the Terai

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Plain, all the products also show a visible discrepancy (Fig. 5). The mean GLASS and SEBAL ET values in this region are about 1000 mm, and ETMonitor has the lowest values (768 mm) (Fig. 5) and other products have a mean value of about 800-900 mm (Fig. 5). The ET estimates are similar for the region with elevation between 2000 and 4500 m. Large ET discrepancies are found in areas above 6,000 m in elevation where some model products (i.e. SSEBop) show ET even exceeding PET (Fig. 5). For example, mean SSEBop ET (749 mm) is higher than other products (<400 mm). However, SSEBop v6 has a significant improvement over the previous version for high elevations.

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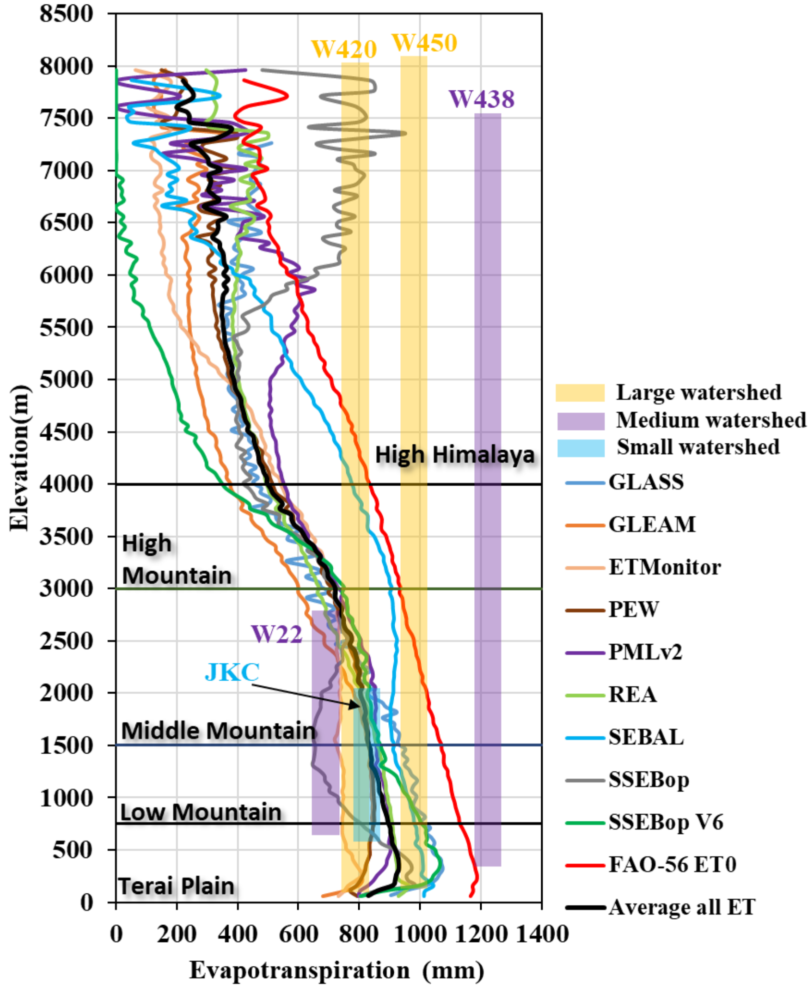

Figure 5. A comparison of characteristics of various annual evapotranspiration products at different altitudes. The yellow, purple, and blue bars represent the elevation ranges of the watersheds used water balance estimation at different scales (yellow, large watershed; purple, middle watershed; blue, small watershed). The positions of these bars on the horizontal axis indicate the long-term average value of water balance for each watershed. Large Watershed: area >10,000 km^2, Middle Watershed: area is between 500 km^2 and 1,000 km^2, Small Watershed: area <500 km^2.

The WaSSI simulated watershed-level mean annual ET rates for the 385 watersheds decrease with rising elevation as well (Fig. 6j). In the Terai Plains, characterized by

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high temperatures and high potential evapotranspiration (PET), the mean annual ET reached 892 mm, substantially lower than PET that exceeded 1200 mm. With rising elevation, temperature declines corresponded to reduced Hamon PET, resulting in an average ET of 844 mm in low mountain regions. Middle mountain regions, benefiting from relatively abundant precipitation and sufficient thermal conditions compared to higher elevations, maintained a mean ET of 764 mm despite further reductions. In high-altitude zones (i.e., High Mountain and High Himalayan regions), diminished PET drove marked decreases in actual ET: mean ET values are 544 mm in high mountain areas and as low as 257 mm in the High Himalayas.

3.4 Spatial and temporal annual ET trend

During 2001-2017, the land area that had an increasing trend of ET_0 and PET as calculated by P-M and Hamon methods were about 37% and 55% of the total area of Nepal, respectively (Fig. S4). However, actual ET trends differed among the eitht ET products.

PMLv2, REA, and SEBAL indicated a upward ET trend in 47%, 69%, and 44% of Nepal, respectively, mostly in higher altitude (>5,000 m) (Fig. 6e, 6f, 6g). In contrast, GLASS exhibited a decrease trend in 33% of the nation (Fig. 6a). The other four ET products show little change in most areas. PMLv2, REA, and SEBAL all showed an upward trend in the middle and high mountain areas near the Gandaki Basin and some parts of the high Himalayas (Fig. 6e, 6f, 6g). The WaSSI simulation results showed an ET increase only in 10% of the country (Fig. 6i). Contratry to the general gloable

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warming and ET_0 and PET rise trend (Fig. S4), GLASS, PEW, and WaSSI suggested that over 10% of the nation showed a decrease trend in ET in eastern part of the country (Fig. 6). The ETMonitor showed no trend in most areas (Fig. 6c), except in regions above 5,000 m (9% of the total area) where ET had an upward trend. Other products (GLEAM, SSEBop) showed little trends (Fig. 6b, h).

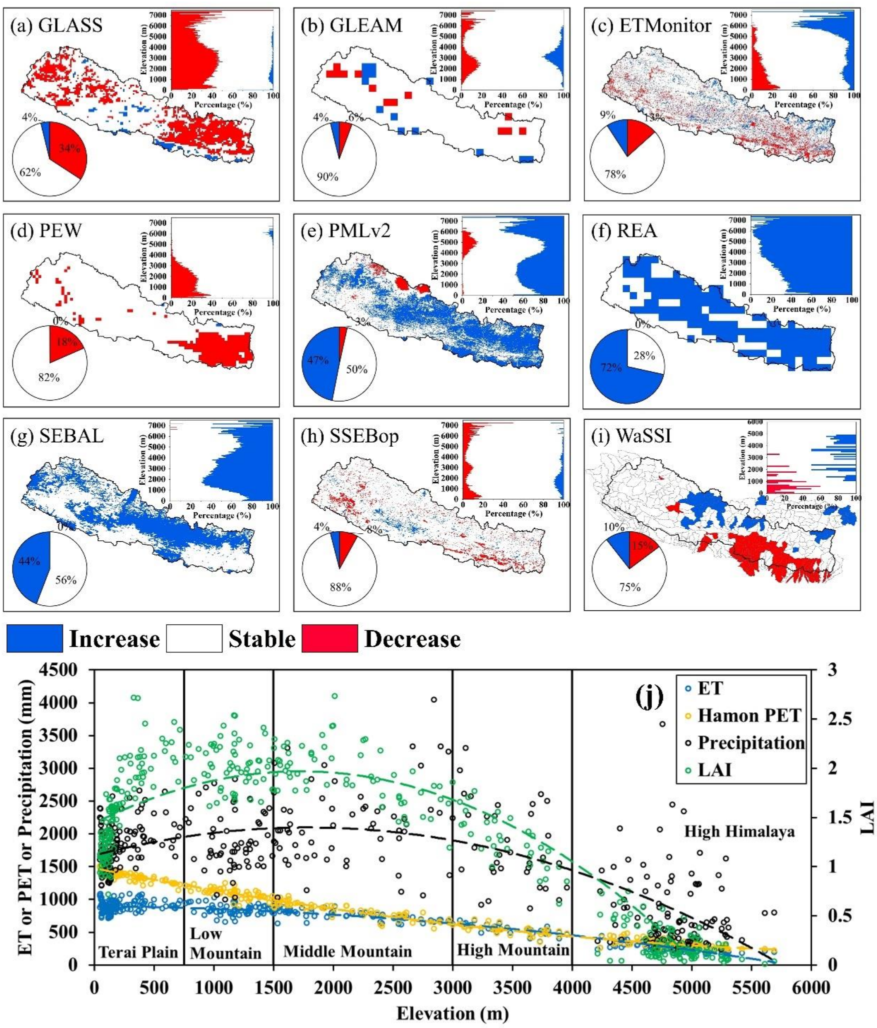

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Figure 6. Mean temporal trend characteristics of different evapotranspiration products with different spatial resolutions across Nepal. SSEBop v6 dataset begins in 2013 and therefore has not been incorporated into long-term trend analyses. The stacked bar chart in the upper right corner of each subplot (a-i) represents the area proportion of ET trends of each product at different elevation, while the pie chart in the lower left corner shows the proportion of different changing trends relative to the total area. (a) GLASS, (b) GLEAM, (c) ETMonitor, (d) PEW, (e) PMLv2, (f) REA, (g) SEBAL, (h) SSEBop, and (i) WaSSI, and (j) The WaSSI simulated ET and associated main model input data of WaSSI (precipitation, LAI), and Hamon PET across an elevation gradient.

3.5 Assessing ET products within the Budyko framework

Comparative analysis using the Budyko framework revealed that all remote sensing products, including the SEBAL model - exhibited significant deviations from the Fu model curve within the Budyko framework (ET/P *vs* PET/P) in high-altitude regions (Fig. 7), indicating pronounced discrepancies in ET estimates for these areas. In contrast, the integrated ecohydrological model (WaSSI) that uses Hamon's temperature-based method to estimate PET demonstrated reasonable performance across the 385 watersheds with ET/P following the Budyko curve as calculated by the Fu model (Fu et al., 1974, 1996; Zhang et al., 2004).

We also assessed the sensitivity of the above results to alternative PET methods used. We replaced PET with the FAO ET_0 (Allen et al., 2007) which is based on the Penaman Monteith (P-M) algorithms and was used by the remote sensing-based models (e.g., SSEBop). We found the issues (i.e., ET>PET) remain (Fig. S3) and PET method options did not improve ET/P vs PET/P patterns at high elevations. Furthermore, the P-M method produced systematically extremely high ET_0/P values ($ET_0/P > 2.0$) in Nepal's high-altitude regions (Fig. S3).

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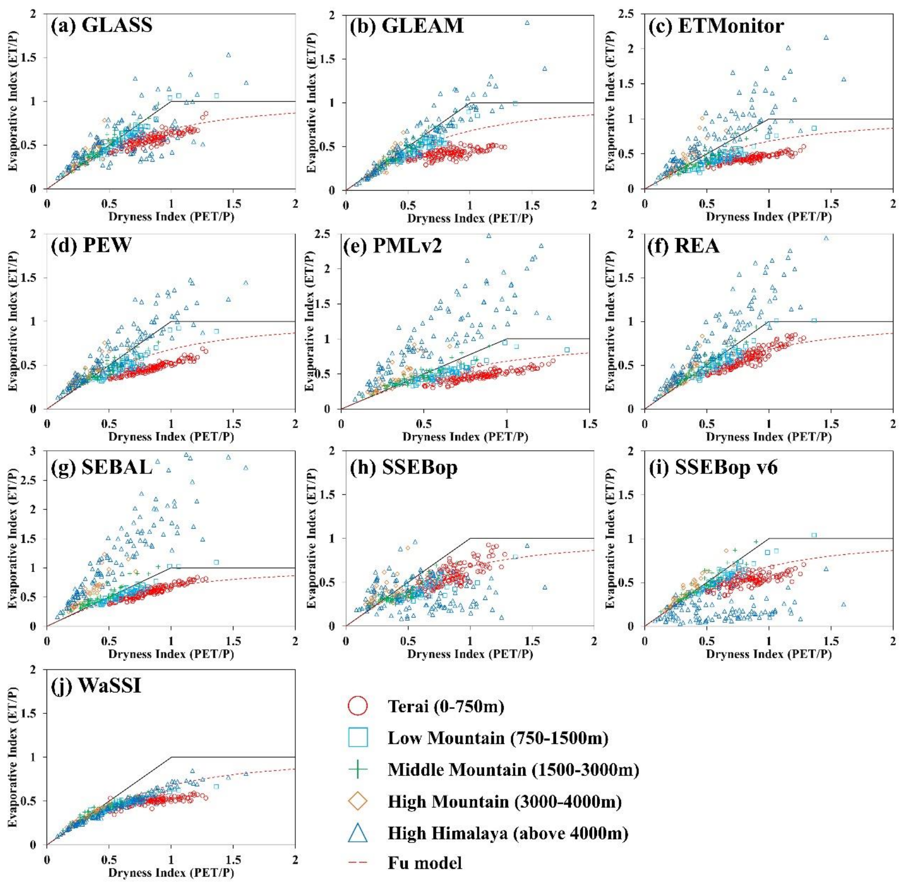

Figure 7. Assessing modeled ET/P *vs* PET/P relationship for eight global ET models and an ecohydrological water balance model (WaSSI) results across an elevation gradient and mountain zones under the Budyko framework. The elevation is classified at a watershed scale for 385 watersheds as used in the WaSSI model (Fig. S2). PET is derived from Hamon method to be consistent among the nine products. Similar comparisons are presented with ET_0 representing as PET calculated by the Penman-Monteith FAO-56 method (See Supplementary Information). (a) GLASS; (b) GLEAM, (c) ETMonitor, (d) PEW, (e) PMLv2, (f) REA, (g) SEBAL, (h) SSEBop; (i) SSEBop v6; (g) WaSSI.

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4 Discussion

4.1 Hydrometeorological data quality issues

Several factors could have contributed to the watershed imbalance issues (i.e., streamflow > precipitation) identified by this study (Fig. 2). These may include significant errors in streamflow measurements and lacking precipitation measurements in higher elevations. In large alpine watersheds, weather stations are mostly installed at low altitudes, and precipitation stations are scarce in high-altitude areas. This could potentially result in underestimates of precipitation at the watershed scale because orographic effects can result in higher precipitation on higher ground and fog formation (Bruijnzeel et al., 2025). Similar studies have pointed out this type of precipitation measurement issues in Himalayas (Miao et al., 2024). For example, reported actual ET in some areas of the Tibetan Plateau exceeds observed precipitation, and runoff coefficients are generally too high (Miao et al., 2024). This is because precipitation measurements in cold regions on high elevations are severely underestimated due to strong winds, and in extreme conditions, and measurement errors can exceed 100% (Miao et al., 2024). Additionally, previous research on precipitation products in the Gandaki Basin found significant discrepancies between observed and gridded product values, as well as between different reanalysis precipitation products (Zeng et al., 2024). Therefore, the uncertainty in precipitation measurements could lead to considerable deviations in ET estimations based on the water balance method for the some of the watersheds, seven out of 12 watersheds in this study. In addition, glacier and frozen soil melting in high elevation watersheds (Nie et al., 2021) may contribute to the observed

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phenomena that streamflow exceeded precipitation. Accuracy of streamflow measurements in high channel gradient streams in mountainous terrains is also often low and questionable in this study (Miao et al., 2024).

In addition, where the calculated watershed-level ET/P based on water balance falls on the Budyko curve is influenced by what PET model is used. This study shows that the option of PET method, the FAO reference ET method (Allen et al., 2007) adopted by SSEBop or the Hamon PET method used by WaSSI could result in differences in detecting ET trend and patterns (Fig. 6, 7). Uncertainty exists in PET estimations that are influenced by the uncertainty of input climate data (e.g. air temperature, radiation, wind speed). This study suggests that cautions must be taken to use the reference ET calculated by the P-M model as PET for a standard use such as by the SSEBop model or other hydrological models for estimating ET.

4.2 Causes for the consistency and discrepancies among ET products

4.2.1 Deficiency of ET model algorithms

Most ET products showed similar results in mid-mountain areas except SEBAL which had notably higher ET than others (Fig. 5). This discrepancy could be due to gap fillings for cloudy days could overestimate ET due to the simple interpolation method for clear-sky days. We argue that sensible heat estimated by SEBAL are most sensitive to the local variables (climate data and remote sensing based LST) (Long et al., 2011). While the effects of mountainous topography on net radiation flux and turbulent processes were incorporated into the SEBAL model simulations in this study, a marked

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overestimation of ET persists in the mid-mountain area. When the difference between the cold and hot pixels in the SEBAL model is too large, the estimated sensible heat flux becomes smaller (Long et al., 2011), resulting in a larger subsequent latent heat flux. Relying solely on vegetation indices as the reference criterion for selecting hot and cold pixels makes it difficult to determine their elevation positions, which may lead to an underestimation of sensible heat flux to some extent. It may be worthwhile to attempt calculating sensible heat flux within elevation intervals where surface temperatures are similar, by setting an elevation threshold. This approach could help reduce the underestimation of sensible heat flux estimates caused by overly large thermal gradients between hot and cold pixels. Therefore, this may be an important reason why SEBAL is overestimated in the mid-mountainous region.

Additionally, this study used MCD12Q1 land cover data as the basis for filling data gaps, which requires relatively high accuracy of the land use dataset. Meanwhile, because temperature in Nepal varies considerably with elevation, the same vegetation may exhibit different growth conditions at different altitudes, adding further uncertainty to the spectral curve fitting. Thus, for future reconstruction of remote sensing data in mountain regions, it is essential to fully consider the spectral characteristics of different vegetation types at different elevations, and to perform gap-filling under approximately similar climatic conditions at the same elevation. Lastly, given Nepal's long monsoon season and frequent cloud cover, the net radiation received by the surface might be lower than estimated, potentially leading to SEBAL's over-estimates in the mid-

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mountain areas. Low land areas are generally influenced by significant human activities, such as irrigation activities (Xue et al., 2006), and most existing ET products primarily account for surface information and land processes, insufficiently considering local human impacts.

Large differences are evident among ET products in high elevations and the lowland Terai plains. The SSEBop model notably overestimates ET in the high elevation regions, with values exceeding PET. This overestimation can be attributed to the accuracy of PET input data in high-altitude areas. The accuracy of SSEBop depends on the precision of input parameters (FAO ET_o and T_s) and the definition of key parameters like the difference between hot and cold boundary difference dT, and wet-bulb T_c (Chen et al., 2016). SSEBop used gridded climate data to determine dT and T_c based on model-defined cold and hot boundaries. However, climate data used in SSEBop V6 is different from SSEBop, and obviously improved ET estimates. Another important parameter used by SSEBop is K_{max}, a scaling coefficient between grass and crop reference ET. It often uses a recommended value of 1.25 (Senay et al., 2020), but K_{max} values should be calibrated using local weather station data (Senay et al., 2013). This calibration is particularly challenging in Nepal, where data are sparse. Furthermore, the ETo dataset used in SSEBop's global products is sourced from the Global Data Assimilation System (GDAS), differing from the meteorological data used in other products, potentially leading to discrepancies among products. Consequently, SSEBop V6 updated the input data: VIIRS data replaced MODIS data and PET data is derived from two PET products,

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TerraClimate dataset (Abatzoglou et al., 2018) and PET maps for Australia (Chiew et al., 2002). The spectral characteristics of VIIRS and MODIS are quite similar (Li et al., 2020; Xiong et al., 2012; Xiong et al., 2022), leading to the inference that the significant difference (Fig. 4, Fig. 6) between SEEBop and SSEBopV6 may be due to differences in other input data, such as PET and climate data. In addition, SSEBop simplifies the influences of aerodynamic processes on sensible heat flux.

Although some ET products use algorithms similar to the Priestley-Taylor (P-T) model (Priestley & Taylor, 1972), there are still significant differences in ET patterns. The sensitivity of these methods to climatic variables could result in uncertainty in areas with uncertain climatic data. The improved P-T models (Fu et al., 2022; Martens et al., 2017; Yao et al., 2013) have been examined to calculate different ET components showing good performance in humid regions because aerodynamic factors have less influence on ET, but the lack of reliable measured radiation data challenges P-T type of model in humid region. The present study primarily considered two factors: the impact of topographical features on radiation (Dubayah, 1992; Yan et al., 2016) and the influence of cloud cover on radiation factors (Kasten & Czeplak, 1980). Nepal's significant elevation differences, with central regions lower than surrounding areas, necessitate consideration of surrounding terrain's impact on net radiation that includes reflected and scattered radiation from surrounding mountains (Wang et al., 2000). It is worth noting that, in addition to differences in algorithmic applicability and model parameters among different models, the remote sensing data used by different products

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also vary. Although it was mentioned above that the spectral characteristics of VIIRS and MODIS are very similar, some scholars have pointed out that the spectral characteristics of other different remote sensing data at different scales exhibit considerable differences, for example, between MODIS and Landsat (Wang et al., 2014). Therefore, Remote sensing data differ considerably as a function of pixel scale, yet the uncertainty in input data can still significantly affect the product results. (Long et al., 2011).

4.2.2 Lack of ground ET observations and biophysical data for model parameterization

The GLASS and REA ET products represent results of integrating multiple ET estimates (Yao et al., 2014; Lu et al., 2021) that heavily rely on eddy flux measurements. Unfortunately, Nepal lacks *in situ* observations such as eddy flux measurements (Joshi et al., 2020), greatly limiting ET model development and validation. The PMLv2 has been validated using on observations from 95 global flux stations (Zhang et al., 2019). However, none of these stations are in Nepal. ETMonitor combines energy balance methods and vegetation physiological parameters to estimate actual ET globally. The model relies on key calibrated parameters like $\gamma_{(s,min)}$ (minimal stomatal resistance for plant transpiration) and K_D (vapor pressure deficit (VPD) stress parameter for plant transpiration) using data from 236 global flux stations (Zheng et al., 2022). However, these research sites for model calibration are mainly in North America and Europe, with few in other regions, insufficiently representing the ecosystem types and climate,

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potentially causing significant bias in the ETMonitor ET results for large watersheds in this study.

The remote sensing-based ET models heavily rely on remotely sensed surface conditions which inherently involve large uncertainty when not corrected with ground truthing, especially for forests (Volk et al., 2023) for leaf area biomass and soil moisture. For instance, ETMonitor uses GLASS leaf area index (LAI) products, while PMLv2 uses MODIS LAI products to calculate ET. Our studies in Nepal have found large discrepancies among LAI products in Nepal (Zhou et al., 2023) although a consistent 'greening up' trend was identified. Recent studies (Nair et al., 2024) have also shown that the importance of input data outweighs that of model parameters. The accuracy of input data affects the calibration of model parameters and can increase the variability in simulation results.

4.3 The necessity of integrated ecohydrological modeling for quantifying ET in data-sparse region

It appears that the relatively simple, uncalibrated ecohydrological model, WaSSI, performs best for estimating annual ET at five selected watersheds that had reasonable quality hydrological measurements, and across 385 watersheds in Nepal as judged by the Budyko principle (Fig. 3, 4). Also, WaSSI performance is exceptionally reasonable for high elevation watersheds where most remote sensing models failed. Seasonal WaSSI ET also show a distinct pattern from most remote sensing products with a narrower but shaper ET curve reflecting the biophysical (i.e., plant phonology, canopy

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conductance) and climate (Monsson climate) controls on ET. Therefore, we argue that modeling regional ET accurately requires an integrated approach that must include local climate (i.e., precipitation, PET), plant dynamics, soil properties (Sun et al., 2011a). Unfortunately, current remote sensing-based ET products primarily rely on surface energy balance and vegetation indices, but might inadequately account for processes such as precipitation partitioning. Although some models partially simulate soil moisture and vegetation transpiration using radar and multispectral remote sensing data, most fail to integrate precipitation, the dominant water input, introducing uncertainties in ET estimation from the initial evapotranspiration phase. For Nepal, a relatively wet region (PET/P<1.0) at annual scale but with extremely high intra-annul variability of precipitation, precipitation emerges as a uniquely critical factor in accurately quantifying national-scale ET.

While the core algorithm of WaSSI is empirically based, its simulation process requires minimal input data without calibration and explicitly incorporates hydrological mechanisms governing precipitation-ET-runoff interactions at the watershed scale. This structural advantage renders WaSSI particularly effective in quantifying regional ET and water yield considering Nepal's data-scarce contexts.

4.3 Changes in ET over space and time: General patterns

Despite the substantial discrepancies in ET trends both horizontally and vertically, and over time among different models (Fig. 6, Fig 7), we have found a few general patterns that characterized the ET dynamics in Nepal. First, ET in high elevation watersheds

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(>4000 m) has been increasing due to global warming (rise of PET), consistent with previous research for the high-altitude areas of the Tibetan Plateau (Chen et al., 2024). The climate of Tibet is becoming warm-wet with the increases of temperature and precipitation (Yu et al., 2024). Studies have found that glaciers in the Himalayas are shrinking in area due to the impacts of climate warming (Nie et al., 2021). Second, actual ET is close to PET in the middle mountain areas where high precipitation and moderate PET favor high ET. Therefore, global warming has the potential to elevate PET and ET in this region. In addition, the middle mountains are 'greening up' due to climate warming and reforestation under the Community Forestry programs (Gao et al., 2023), further increasing ET at the national level. Third, WaSSI ET has showed a decrease trend in some of the Low Mountain and Terai Plain regions (elevation <1500 mm) in eastern part of the Nepal where water stress was prevalent (ET/PET<1.0) and precipitation was reportedly indeed decreasing. Our previous study suggests that the relatively dry western region of Nepal has become wetter, and the relatively wet eastern region has become drier post-2003 (Luo et al., 2023). Finally, monthly ET peaked in July-August in areas below elevation of 3000 m in Nepal corresponding to a period with high PET and precipitation. Annual ET varied widely between roughly 600-1100 m for watersheds below elevation 3000 m confirming the large influence of elevation on water balances in the Lesser Himalayas (Middle Mountains).

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4.4 Future ET studies in Nepal

To our knowledge, this study represents the first comprehensive attempt to quantify ET across Nepal. Nepal is a typical data-scarce region, and water imbalance occurs in some basins. In this context, introducing the Budyko framework to evaluate different model products helps alleviate uncertainty to some extent in watershed scale, and also provides an approach for model evaluation in other data-scarce regions. We show that accurate input data are essential for accurately estimating ET at multiple scales and assess existing ET models developed elsewhere. Meteorological (i.e., precipitation, temperature, radiation) and land surface characteristics (e.g., LST, LAI) directly affect ET estimates (Sun et al., 2011a). Cloud and fog deposition in mountainous areas can affect actual precipitation inputs (Bruijnzeel et al., 2011; Vogelmann et al., 1968; Vogelmann, 1973; Holder, 2004). Accurate measurement of precipitation in Nepal is essential for estimating water balance components (Talchabhadel & Chhetri, 2024), as it greatly influences watershed-scale ET estimates. Additionally, lack of small watershed monitoring and eddy flux observations (Amataya et al., 2015; Amataya et al., 2016; Joshi et al., 2020; Mukherjee et al., 2021) in the Himalaya region limits optimizing existing ET model parameterization and developing new models that fit local conditions.

The global ET products use meteorological data from various sources (Fu et al., 2022). The uncertainty of ET estimates stems from both differences in input data sources and variations in model algorithms. (Volk et al., 2024). Ensuring accurate meteorological

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observations allows for future comparisons of existing mainstream gridded meteorological products to select the most suitable climate and ET products for Nepal.

There are also rooms for improvement in the algorithms used by different ET approaches. For high-altitude areas with cold climates and intense convection, it is necessary to reassess the applicability of some ET algorithms to understand why the ET was over estimated. New models or coupled models suitable for extreme climate conditions should be selected or developed to achieve accurate estimates in Himalaya region. For surface energy balance models, accurately estimating ET requires quantifying cloud and improving estimates of solar radiation. Net radiation has influences on the uncertainty for actual ET calculation for humid regions (Li et al., 2024). During the monsoon season, Nepal frequently experiences cloud cover, and remote sensing methods for estimating net radiation typically calculate clear-sky radiation, which can differ from actual surface-received radiation, introducing uncertainty to ET results. Future studies should develop mathematical relationships between ground-based observed net radiation and remotely sensed net radiation to correct remote sensing product estimations. Over complex terrain, parameterization schemes should be designed to explicitly account for elevation variations in LST and differences in vegetation types. Although the WaSSI is considered a success for estimating watershed-level ET across Nepal, future validation is needed to refine the empirical ET algorithms that were developed outside of the Himalaya regions to reflect the true ecosystem ET processes in Nepal (Ghimire et al., 2014a, b).

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For 'data poor' regions such as Nepal, establishing a reliable hydrological and meteorological observation network is crucial to estimate ET at multiple scales and parameterizing global ET models identified by this study and other hydrological models (Sun et al., 2025) including MIKE SHE (Andersen et al., 2001) and SWAT (Dhami et al., 2018), InVest (Bastola et al., 2019) that have been widely used in Nepal. Future field-based studies need to examine how water input from glacier melt or frozen soils impacts the water balance in medium to large sized watersheds covering high elevations in Nepal to close the water budgets (Steiner et al., 2021). A recent study (Li et al., 2024) has pointed out that the accuracy of ET over homogeneous surfaces is relatively high compared to moderately and highly heterogeneous surfaces. This presents a challenge for establishing observation stations in the mountains in Nepal. In addition, when establishing eddy flux and forest hydrological observation sites (Bruijnzeel et al., 2024), it is essential to consider Nepal's typical vegetation characteristics, such as land cover and land use type and history along a large elevation gradient.

5. Conclusions

Using national monitored hydrometeorological data for multiple watersheds this study evaluated eight global ET products and an ecohydrological model at a watershed scale and across different altitudes in Nepal. We reveled a large uncertainty in the observation data that hamper model assessment. The global ET products likely overestimate ET at High Mountains and do not agree on the general temporal and spatial distributions (laterally and vertically over altitude). However, collectively, these models suggest a

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possible increasing trend in ET in some of the high-altitude regions due to global warming. ET rates generally decrease with an increase in elevation, but variabilities among the products were more pronounced at both high and low altitude regions. We conclude that these remote sensing products are relatively reliable for the Middle Mountains in Nepal. However, we caution using existing global ET products for hydrological modeling and water balance resource management planning in high mountain regions. We also conclude that the integrated ecohydrological model WaSSI is preferred to estimate monthly watershed ET and water yield across Nepal when modeling resources are available.

Future research is needed to better evaluate the monitoring data and assess ET model applications in a complex terrain. Adding more weather stations is likely to improve mapping precipitation, thus improve the water budget and better quantify PET for high elevations where meting glaciers dominate the hydrologic change under climatic warming. More direct measurements of ecosystem ET (e.g., eddy flux, sapflow, canopy interception) in the middle mountains where land use and land cover are changing rapidly (i.e., 'greening up' or urbanization) is essential to develop reliable ET models for Nepal. Basic ecohydrological research is essential for validating global hydrology products that are developed outside of the Lesser Himalaya region. Outcomes from this comprehensive study provide enhanced understanding of ET variations and improved estimates of ET across Nepal.

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Data Availability Statement

Data sets used for this study were obtained from several published sources:

Data	References
Precipitation	http://www.dhm.gov.np/
Runoff	http://www.dhm.gov.np/
DEM	https://search.earthdata.nasa.gov
MOD09A1 (band 1 – 5 and band 7)	https://lpdaac.usgs.gov
MCD12Q1 (band 1, IGBP)	https://lpdaac.usgs.gov
High-resolution near-surface meteorological forcing dataset for the Third Pole region (TPMFD)	(Jiang et al., 2023) https://data.tpdc.ac.cn
Thermal and Reanalysis Integrating Moderate - resolution Spatial - seamless LST – Tibetan Plateau (TRIMS LST-TP)	(Zhang et al., 2021) https://data.tpdc.ac.cn
Global Land Surface Satellite (GLASS)	(Yao et al., 2014) http://www.glass.umd.edu/
Global Land Evaporation Amsterdam Model (GLEAM)	(Miralles et al., 2011) https://www.gleam.eu/
ETMonitor Global Actual Evapotranspiration Dataset (ETMonitor)	(Zheng et al., 2022) https://data.tpdc.ac.cn
Proportionality hypothesis-based surface Energy-Water Balance model (PEW)	(Fu et al., 2022) https://data.tpdc.ac.cn
Penman-Monteith-Leuning (PMLv2)	(Zhang et al., 2019) https://earthengine.google.org
Reliability Ensemble Averaging (REA)	(Lu et al., 2021) https://data.tpdc.ac.cn
Surface Energy Balance Algorithm for Land (SEBAL)	(Bastiaanssen et al., 1998)
Operational Simplified Surface Energy Balance model parameterized (SSEBop)	(Senay et al., 2013) https://earlywarning.usgs.gov/
Operational Simplified Surface Energy Balance model parameterized Version 6 (SSEBop V6)	(Senay et al., 2023) https://earlywarning.usgs.gov/

Author contributions

K.J.: Data curation, Formal analysis, Methodology, Software, Validation, Writing - original draft, Writing - review & editing. L.H.: Conceptualization, Funding acquisition, Project administration, Supervision, Writing - original draft, Writing - review & editing.

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Competing interests

The authors declare that they have no conflict of interest.

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