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Title

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Conflict of Interest

The authors declare no conflicts of interest.

Ethics Statement

This study did not involve human participants or animal experimentation. The research was conducted using meteorological/remote-sensing data and therefore did not require approval from a human research ethics committee or an animal care and use committee.

Author Contributions

Mulatu Ayalew: Conceptualization; Methodology; Investigation; Formal analysis; Writing – original draft.

Balew Yeneneh: Resources; Supervision; Writing – review & editing.

Muktar Asmamaw: Resources; Supervision; Writing – review & editing.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of AI Use

The authors acknowledge the use of generative artificial intelligence (AI) tools to improve the clarity, language, and flow of this manuscript. Following the use of these tools, the authors reviewed, edited, and revised the output to ensure accuracy and take full responsibility for the final content of this publication.

ABSTRACT

Evapotranspiration (ET) is a fundamental component of the hydrological cycle that simultaneously integrates interactions between land surface, vegetation, and atmospheric systems through the combined processes of evaporation and transpiration. This is especially critical in arid and semi-arid regions such as Quara District in northwest Ethiopia, where water resources are scarce and precise quantification of actual water consumption is essential for sustainable water management. This study applies the Surface Energy Balance Algorithm for Land (SEBAL) model using Landsat-8 OLI/TIRS remote sensing imagery acquired during the dry season of 2020 (January, February, March, and April) to estimate actual evapotranspiration (ET) across the Quara District. The SEBAL model computes ET as a residual of the surface energy balance equation, requiring estimation of net radiation (R_n), soil heat flux (G_0), and sensible heat flux (H). The results reveal ET₂₄ values ranging from 0.68 mm/day to 9.63 mm/day across the four acquisition dates, with pronounced spatial and temporal variability driven by differences in land cover type, soil moisture, and vegetation density. The methodology demonstrates that satellite-based energy balance models offer a robust, spatially explicit alternative to traditional ground-based methods for ET estimation in data-scarce environments. The findings underscore the value of integrating remote sensing and GIS techniques for operational water resources management in semi-arid landscapes.

Keywords: Evapotranspiration, SEBAL, remote sensing, Landsat-8, surface energy balance, Quara District, Ethiopia

1. INTRODUCTION

Evapotranspiration (ET) represents one of the most complex and simultaneously essential components of the terrestrial hydrological cycle. It encompasses both the physical process of evaporation from soil and water surfaces and the biological process of transpiration from vegetation, collectively returning water from the land surface to the atmosphere (Tschinkel, 1972). ET is controlled by multiple interacting factors including solar radiation, air temperature, humidity, wind speed, soil moisture availability, and vegetation characteristics (Khalil et al., 2020). In agricultural regions, ET represents the largest component of water consumption, making its accurate estimation indispensable for irrigation scheduling, crop water requirement assessment, and regional water balance studies (Yilmaz et al., 2020).

The study area, Quara District, is located in the North Gondar Zone of Amhara National Regional State in northwest Ethiopia. It is situated between latitude 11°30'N and 12°30'N and longitude 35°25'E and 36°35'E, with a total land area of approximately 2,130 km² (Mewa, 2018). The district lies in a semi-arid climatic zone characterized by unimodal rainfall concentrated in the summer months (June to September), with an annual precipitation ranging from 800 to 1,400 mm (Ali & Meshesha, 2018). The dry season extends from October through May, during which high temperatures and low humidity create conditions conducive to substantial water loss through evapotranspiration (Mewa et al., 2018).

Traditional methods for estimating ET include meteorological approaches such as the Penman-Monteith method (Allen et al., 1998), which rely on point-based weather station measurements. However, these methods are limited by their inability to capture spatial heterogeneity, particularly in landscapes with diverse land cover types and complex topography. Remote sensing techniques offer a transformative alternative by providing spatially continuous, temporally repeatable, and cost-effective data for estimating ET over large areas (Gorelick et al., 2017). Among various remote sensing-based approaches, the Surface Energy Balance Algorithm for Land (SEBAL) has gained prominence for its operational applicability and its ability to estimate actual ET without requiring detailed ground measurements of vegetation and soil parameters (Bastiaanssen et al., 1998; Allen et al., 2007).

Despite the critical importance of ET estimation in arid and semi-arid regions, there remains a significant gap in the application of remote sensing-based methods for water resource management

in rural Ethiopia. The Quara District, like many areas in the country, faces challenges including inadequate water infrastructure, agricultural water scarcity, and limited availability of meteorological data at the spatial resolution required for watershed-level management (Birhanu et al., 2018). The integration of remote sensing and GIS-based techniques has not been systematically applied to quantify ET in this region, leaving a knowledge gap that hinders evidence-based water resources planning. The objective of this study is to estimate evapotranspiration using the SEBAL model based on remote sensing and GIS techniques in the Quara District. The findings of this study contribute directly to the growing body of evidence supporting satellite-based ET estimation as a viable tool for water resource management in data-scarce environments. By demonstrating the operational applicability of the SEBAL model in the Quara District, the study provides a replicable methodology that can be applied to other semi-arid regions of Ethiopia and the broader Horn of Africa. The spatially explicit ET maps generated can inform agricultural extension services, water management authorities, and policymakers on water consumption patterns, enabling more targeted irrigation planning, drought monitoring, and sustainable water allocation strategies. Furthermore, the validation of SEBAL-derived ET against the FAO Penman-Monteith method provides a quantitative assessment of model accuracy, strengthening confidence in satellite-based ET products for regional-scale applications.

2. MATERIALS AND METHODS

2.1 Study Area

Quara District is located in the North Gondar administrative zone of the Amhara National Regional State in northwest Ethiopia. Geographically, it lies between approximately latitude 11°30'N and 12°30'N and longitude 35°25'E and 36°35'E (Figure 1). The district covers a total area of about 2,130 km² (approximately 213,000 hectares) and is situated at elevations ranging from approximately 800 m to 1,800 m above mean sea level (Mewa et al., 2018). The topography is characterized by relatively flat plains in the western part, transitioning to rugged terrain and highlands in the eastern portion. The major river systems include the Tekeze River and its tributaries, which provide the primary surface water resources for the district.

The climate of Quara District is classified as tropical semi-arid (Köppen climate classification: BSh), with distinct wet and dry seasons. The rainy season extends from June to September, with the highest precipitation occurring in July and August. The dry season spans from October through May, during which potential evapotranspiration significantly exceeds precipitation (Mewa, 2018).

The annual temperature ranges from approximately 14°C to 42°C, with the highest temperatures occurring during the pre-monsoon months of April and May. The annual rainfall varies between 800 and 1,400 mm, with considerable inter-annual variability driven by the El Niño-Southern Oscillation (ENSO) and other regional climate patterns (Ali & Meshesha, 2018).

The vegetation cover is dominated by open grassland, sparse woodland, and cultivated agricultural areas. The primary land use activities include smallholder subsistence farming, livestock grazing, and limited commercial agriculture. The major crops grown during the rainy season include sorghum, maize, teff, and various legumes. During the dry season, irrigated agriculture is practiced in areas with access to river water, predominantly producing vegetables and fodder crops.

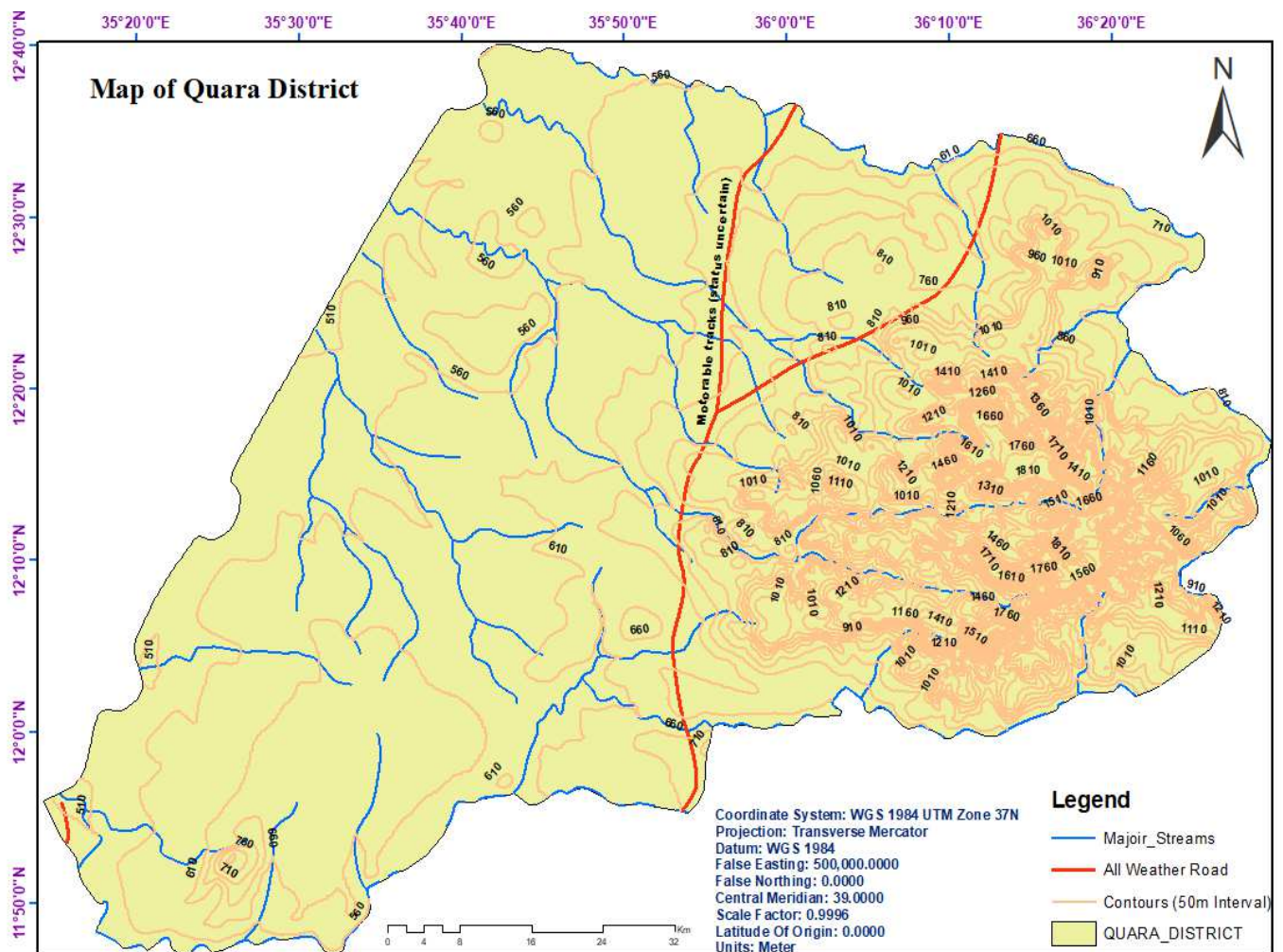


Figure 1. Location Map of the Quara District (Source: CSA Shape File, 2012)

2.2 Data Sources and Acquisition

The study employed four categories of data: (1) satellite remote sensing imagery, (2) meteorological data, (3) topographic data, and (4) soil data.

Remote sensing data: Cloud-free Landsat-8 OLI/TIRS (Operational Land Imager / Thermal Infrared Sensor) Level-1 products were downloaded from the USGS Earth Explorer portal for four dates during the dry season of 2020: January 12, 2020; February 8, 2020; March 10, 2020; and April 24, 2020. The Landsat-8 imagery provides nine multispectral bands with a 30-meter spatial resolution for the visible, near-infrared, and short-wave infrared bands, plus one panchromatic band at 15-meter resolution and two thermal infrared bands at 100-meter resolution (which are resampled to 30-meter resolution in the pre-processing stage). The spectral characteristics of the bands are summarized in Table 1.

Table 1. Landsat-8 OLI/TIRS spectral band characteristics.

Band	Wavelength (μm)	Spatial Resolution (m)	Primary Application
Band 1 – Coastal/Aerosol	0.433–0.453	30	Aerosol detection, water quality
Band 2 – Blue	0.450–0.515	30	Water body penetration, bathymetry
Band 3 – Green	0.525–0.600	30	Vegetation health assessment
Band 4 – Red	0.630–0.680	30	Vegetation discrimination
Band 5 – NIR	0.845–0.885	30	Biomass estimation, vegetation vigor
Band 6 – SWIR 1	1.560–1.660	30	Soil moisture, vegetation stress
Band 7 – SWIR 2	2.100–2.300	30	Geological mapping, soil moisture
Band 8 – Panchromatic	0.500–0.680	15	Spatial resolution enhancement
Band 9 – Cirrus	1.360–1.390	30	Cirrus cloud detection
Band 10 – TIRS 1	10.60–11.19	100 (30 resampled)	Thermal mapping, land surface temperature
Band 11 – TIRS 2	11.50–12.51	100 (30 resampled)	Thermal mapping, land surface temperature

Meteorological data: Daily meteorological observations including maximum and minimum air temperature, relative humidity, wind speed, and sunshine hours were obtained from the Ethiopian National Meteorological Agency (NMA) service station in Bahir Dar for the period corresponding to the satellite overpass dates. These data were used for the validation of SEBAL-derived ET against the FAO Penman-Monteith reference evapotranspiration (ET_0) and for calibrating certain SEBAL parameters.

Topographic data: The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with 30-meter spatial resolution was used to derive slope and aspect information, which are required for calculating the solar incident angle and its influence on net radiation.

Soil data: The Harmonized World Soil Database (HWSD) was used to obtain soil texture information, including sand, silt, and clay content percentages, which are relevant for computing soil heat flux and thermal properties.

2.3 Estimating Evapotranspiration

2.3.1 Instantaneous Evapotranspiration (ET_{inst})

The instantaneous evapotranspiration ET_{inst} for the satellite at the crossing time above the study area (Toulios et al., 2013). ET_{inst} at satellite pass time was computed using equation 3.1.29:

$$ET_{inst} = 3600 (\lambda ET / \lambda \rho_w) \dots \dots \dots \text{eq.3.1.29}$$

where; ET_{inst} is the instantaneous ET (mm/hr), 3600 is the time conversion from seconds to hours, λET is latent heat flux (W/m^2), ρ_w is the density of water (10^3 kg/m^3), and λ Latent heat of vaporization (J/Kg) by (British et al., 2002) when a kilogram of water evaporates is computed using equation 3.1.30:

$$\lambda = [2.501 - 0.002361(T_s - 273.15)] \times 10^6 \text{ J/kg} \dots \dots \dots \text{eq.3.1.30}$$

(Note: since λ is in J/Kg and ET_{inst} is in mm/hr there is a need to equate the units)

2.3.2 Reference Evapotranspiration Estimation by FAO-PM Method

The FAO Penman-Monteith method was derived from the original Penman-Monteith equation in combination with the equations of aerodynamic and surface resistance. As argued by Allen et al. (2011), though RS-based methods can provide reasonable results, it is recommended to be tested by ground observation datasets. Hence, to validate RS-based, SEBAL model ET value is estimated by using the FAO-PM technique.

The primary reason why the FAO Penman method opts for the study was that it has the capability of yielding correct ET_r values under a wide range of surface characteristics and climatic conditions with consistency even when there exists data scarcity. The Penman-Monteith equation was applied to derive actual evapotranspiration using the meteorological dataset within the study area (Allen et al., 1998), and it is recommended as the sole method for determining reference evapotranspiration (ET_r). Therefore, according to Bektaş Balçık, et al. (2020), the FAO Penman method is used to compute the (ET_r) by using equation 3.1.31:

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \dots\dots\dots \text{eq.3.1.31}$$

Where, ET_r is the reference evapotranspiration values (mm day^{-1}), R_n is net radiation (W/m^2), G is the soil heat flux (W/m^2), γ is the psychrometric constant ($\text{kPa/}^\circ\text{C}$), T is the mean daily air temperature ($^\circ\text{C}$), U_2 is the wind speed (m/s) at the local station which considered as 2-meter height, e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the saturation pressure curve ($\text{kPa/}^\circ\text{C}$).

2.3.3 Reference Evapotranspiration Fraction (ET_rF)

The Reference ET Fraction (ET_rF) is defined as the ratio of the computed instantaneous evapotranspiration (ET_{inst}) for each pixel to the reference evapotranspiration (ET_r) computed from weather data at the image pass time. It is similar to a well-known crop coefficient and is used to extrapolate ET from the imaging time to 24-hour or longer periods. Generally, ET_rF values range from 0 to 1.5 and are assumed to be constant during the day depending on the self-preservation process in main surface energy balance components on the daily basis.

The ET_rF for a pixel representing dry soil can be close to zero, a dry pixel has $ET = 0$ and $ET_rF = 0$, and a wet pixel with full vegetation cover can occasionally have an ET slightly greater than ET_r and therefore $ET_rF > 1$. However, ET_r generally represents an upper bound on ET for large expanses of well-watered vegetation. Since several assumptions were made for the computation of various variables, especially sensible heat flux, negative values can be expected. ET_rF value of 1.0 means that the fraction of reference ET is 1.0. so that the ET for that pixel equals the reference evapotranspiration (ET_r) value.

The ET_rF evaporative fraction can be computed by using equation 3.1.32.

$$ET_rF = \frac{ET_{inst}}{ET_r} \dots\dots\dots \text{eq.3.1.32}$$

Where: $ET_r F$ is the Reference Evapotranspiration fraction, ET_{inst} is the instantaneous ET (mm/hr) from equation 3.1.29, and ET_r is the reference evapotranspiration (mm/day) from equation 3.1.31.

2.3.4 Actual Daily Evapotranspiration (ET_{24})

Daily evapotranspiration is the depth of water (mm/day) lost as a vapour to the atmosphere during the 24 hours of a day from the soil, water, and vegetation surfaces. SEBAL computes the instantaneous energy fluxes and ET for the satellite overpass time. These instantaneous values are then extrapolated to daily and long-period values by using the evaporative fraction. Daily values of ET (ET_{24}) are often more useful than instantaneous ET. SEBAL computes the ET_{24} by assuming that the instantaneous $ET_r F$ computed in equation 3.1.32 is the same as the 24-hour average. Assuming the instantaneous evaporative fraction is equivalent to its daily average value, ET_{24} can be calculated by using the evaporative fraction and reference evapotranspiration (ET_r), as stated by (Allen et al., 2011; Al-Sulttani et al., 2016b).

Actual daily evapotranspiration (ET_{24}) can be computed by using equation 3.1.33:

$$ET_{24} = ET_r F * ET_{r_24} \dots\dots\dots \text{eq.3.1.33}$$

Where; ET_{24} is the Actual daily evapotranspiration, $ET_r F$ is the daily average evaporative fraction and ET_{r_24} is the cumulative 24-hour ET_r for the day of the image.

Daily ET_r was computed by the FAO Penman-Monteith formula based on the weather data i.e., temperature, sunshine hours, wind speed, and relative humidity of the weather stations.

$$ET_{r_24} = \sum_h^{24} ET_r - h \dots\dots\dots \text{eq.3.1.34}$$

Where; ET_{r_24} is cumulative 24-hour ET_r for a day, h is an hour.

2.4 Overview of the SEBAL Model

The Surface Energy Balance Algorithm for Land (SEBAL) is a remote sensing-based energy balance model originally developed by Bastiaanssen et al. (1998) and subsequently refined for operational applications (Allen et al., 2007; Tasumi et al., 2008). SEBAL estimates actual evapotranspiration (ET) as the residual term of the surface energy balance equation, which is derived from the fundamental law of conservation of energy at the Earth's surface. The model has been successfully applied across diverse climatic and agricultural regions worldwide, including

the Nile Basin (Bastiaanssen, 2000), the western United States (Allen et al., 2007), and the Sahel region of Africa (Garcia et al., 2013).

The core principle of SEBAL is that the net energy available at the land surface (R_n) is partitioned into three main fluxes: soil heat flux (G_0), sensible heat flux (H), and latent heat flux (LE), which represents evapotranspiration. The surface energy balance equation is expressed as:

$$R_n = G_0 + H + LE$$

From this equation, the latent heat flux can be estimated as the residual:

$$LE = R_n - G_0 - H$$

The instantaneous latent heat flux (LE) is then converted to the actual evapotranspiration rate (ET_{inst}) using the latent heat of vaporization (λ):

$$ET_{inst} = LE / \lambda$$

Finally, the instantaneous ET is extrapolated to a daily (24-hour) ET value using the ratio of daily net radiation to instantaneous net radiation and the ratio of daily to instantaneous evapotranspiration fractions (the evaporative fraction, Λ):

$$ET_{24} = (\Lambda \cdot 24 \cdot 3600 \cdot R_n \text{ daily}) / (\lambda \cdot 10^6)$$

where ET_{24} is the daily evapotranspiration in mm/day, R_n daily is the daily net radiation in MJ/m²/day, and λ is the latent heat of vaporization in J/kg.

2.5 Computation of Surface Energy Balance Components

Figure 2 presents the components of the surface energy balance, including net radiation, soil heat flux, sensible heat flux, and latent heat flux, which form the basis of the SEBAL computations described below.

Land-atmosphere interactions: Surface energy balance

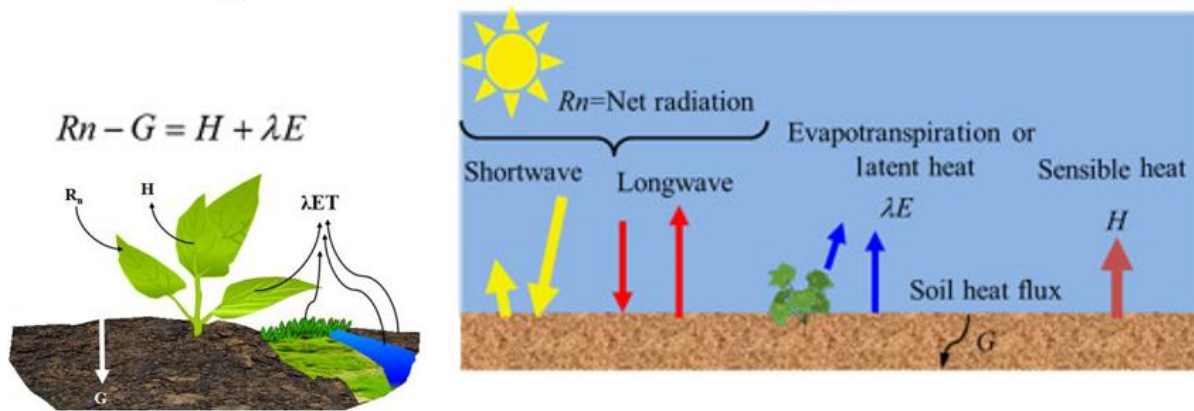


Figure 2.Components of Surface Energy Balance

2.5.1 Net Radiation (R_n)

Net radiation (R_n) represents the balance between incoming and outgoing shortwave and longwave radiation at the Earth's surface.

The surface radiation balance used to derive R_n is illustrated in Figure 3.

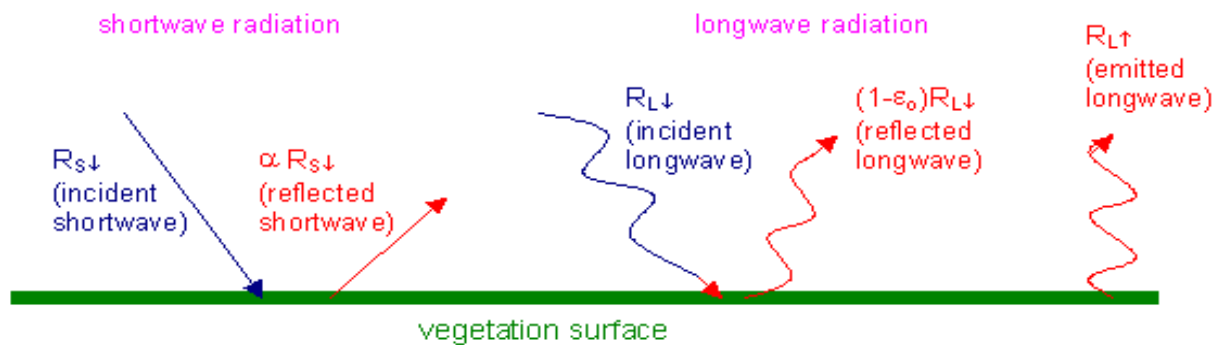


Figure 3.Surface radiation balances of available net radiation (R_n)

It was computed as:

$$R_n = (1 - \alpha) \cdot R_{S\downarrow} + \epsilon_a \cdot \sigma \cdot T_a^4 - \epsilon \cdot \sigma \cdot T_s^4$$

where α is the surface albedo (dimensionless), $R_{S\downarrow}$ is the incoming shortwave solar radiation (W/m^2), ϵ_a is the atmospheric emissivity, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} W/m^2/K^4$), T_a is the near-surface air temperature (K), ϵ is the land surface emissivity, and T_s is the land surface temperature (K).

The surface albedo (α) was computed as a weighted average of the spectral reflectance values from the visible, near-infrared, and short-wave infrared bands of Landsat-8:

$$\alpha = \sum_{i=1}^n w_i \cdot \rho_i$$

where w_i are the spectral weighting factors derived from the relative spectral response of each band, and ρ_i are the TOA reflectance values for each band. Narrowband-to-broadband conversion coefficients were applied to account for the difference between the narrow spectral bands of Landsat-8 and the broadband albedo.

The incoming shortwave solar radiation ($R_{s\downarrow}$) was computed using the solar constant, the Earth-Sun distance, and the solar incident angle derived from the solar elevation angle, latitude, longitude, and acquisition date/time:

$$R_{s\downarrow} = G_{sc} \cdot \cos(\theta) \cdot d_r \cdot \tau_{sw}$$

where G_{sc} is the solar constant (1367 W/m²), θ is the solar incidence angle, d_r is the relative Earth-Sun distance, and τ_{sw} is the shortwave atmospheric transmissivity estimated from the atmospheric visibility or from the DEM-derived elevation and the local atmospheric conditions.

The atmospheric emissivity (ε_a) was estimated using the empirical relationship based on atmospheric vapor pressure and air temperature (Brutsaert, 1975):

$$\varepsilon_a = 1.24 \cdot (e_a / T_a)^{(1/7)}$$

where e_a is the actual vapor pressure (hPa) and T_a is the air temperature in Kelvin.

2.5.2 Soil Heat Flux (G_0)

Soil heat flux (G_0) represents the rate of heat transfer into the soil. It is typically a small fraction of net radiation, particularly over fully vegetated surfaces. In SEBAL, G_0 is estimated as a fraction of net radiation based on the surface albedo, vegetation indices, and surface temperature (Bastiaanssen et al., 1998):

$$G_0 = R_n \cdot (T_s \cdot 0.0038 + 0.0074 \cdot (1 - 0.98 \cdot NDVI^4)) \cdot (1 - 0.98 \cdot NDVI^4)$$

This empirical relationship accounts for the fact that bare soil surfaces have higher soil heat flux relative to net radiation than vegetated surfaces. For areas with dense vegetation ($NDVI > 0.7$), G_0 is typically less than 5% of R_n , while for bare soil areas, G_0 can reach 20–30% of R_n .

2.5.3 Sensible Heat Flux (H)

The sensible heat flux (H) represents the heat transfer from the surface to the atmosphere through convection and conduction. It is computed using the aerodynamic resistance approach and requires an iterative process to solve for the temperature gradient between the surface and the near-surface atmosphere (Bastiaanssen et al., 1998; Allen et al., 2007):

$$H = \rho_{\text{air}} \cdot c_p \cdot dT / r_{\text{ah}}$$

where ρ_{air} is the air density (kg/m^3), c_p is the specific heat capacity of air at constant pressure ($1004 \text{ J/kg}\cdot\text{K}$), dT is the temperature difference between the surface and the near-surface air (K), and r_{ah} is the aerodynamic resistance to heat transfer (s/m).

The key innovation of SEBAL lies in the internal calibration of dT using the extreme temperature pixels: the "cold pixel" (well-watered vegetation with low sensible heat flux, $H_{\text{cold}} \approx 0$) and the "hot pixel" (dry bare soil with no evapotranspiration, $H_{\text{hot}} = R_n - G_0$). These anchor pixels are identified automatically from the image by selecting pixels with maximum NDVI (cold pixel) and minimum NDVI (hot pixel) within a buffer around agricultural areas.

A linear relationship between dT and land surface temperature (T_s) is established using the two anchor pixels:

$$dT = a \cdot T_s + b$$

where a and b are the slope and intercept coefficients derived from the cold and hot pixel conditions. This linear relationship is then applied to all pixels in the image to estimate dT and subsequently H .

The aerodynamic resistance to heat transfer (r_{ah}) is computed using the Monin-Obukhov similarity theory, accounting for atmospheric stability conditions (neutral, stable, or unstable) through the iterative correction of the friction velocity (u_*) and the displacement height (d) and roughness length (z_{om}) for momentum and heat (z_{oh}):

$$r_{\text{ah}} = 1 / (u_* \cdot k) \cdot \ln((z_{\text{om}} - d) / z_{\text{oh}})$$

where k is the von Kármán constant (0.41), and u_* is the friction velocity derived from the wind speed at the blending height. This iterative process is critical for obtaining accurate H estimates,

especially in heterogeneous landscapes where the surface roughness varies significantly between bare soil and vegetated areas.

2.6 Conversion from Instantaneous to Daily ET

The SEBAL model computes the instantaneous latent heat flux (LE) at the satellite overpass time. To extrapolate this to a daily ET value, the evaporative fraction (Λ) approach is used. The evaporative fraction is defined as the ratio of latent heat flux to the available energy (net radiation minus soil heat flux):

$$\Lambda = LE / (R_n - G_0) = LE / (LE + H)$$

The evaporative fraction is assumed to be relatively constant over a diurnal cycle under the assumption that the partitioning of available energy between latent and sensible heat fluxes is primarily driven by surface conditions (soil moisture, vegetation) that do not change significantly over a single day. This assumption has been validated in numerous studies across diverse climates (Bastiaanssen et al., 2005; Allen et al., 2007).

The daily latent heat flux (LE₂₄) is then estimated as:

$$LE_{24} = \Lambda \cdot (R_{n,24} - G_{0,24})$$

where $R_{n,24}$ and $G_{0,24}$ are the daily net radiation and daily soil heat flux, respectively. Daily net radiation is estimated using the instantaneous net radiation and the ratio of daily to instantaneous solar radiation, or using meteorological models. Daily soil heat flux is often assumed to be negligible at the daily scale over vegetated surfaces, or estimated using the fraction of daily net radiation based on land cover type.

The daily ET in depth units (mm/day) is computed as:

$$ET_{24} = (LE_{24} \cdot 86400) / (\lambda \cdot \rho_w \cdot 10^6)$$

where 86400 is the number of seconds in a day, λ is the latent heat of vaporization (approximately 2.45 MJ/kg at 20°C), and ρ_w is the density of water (1000 kg/m³). The factor 10⁶ converts MJ to J, yielding the final ET in mm/day.

The overall workflow followed in this study, from image acquisition and pre-processing through SEBAL computation, is summarized in Figure 4.

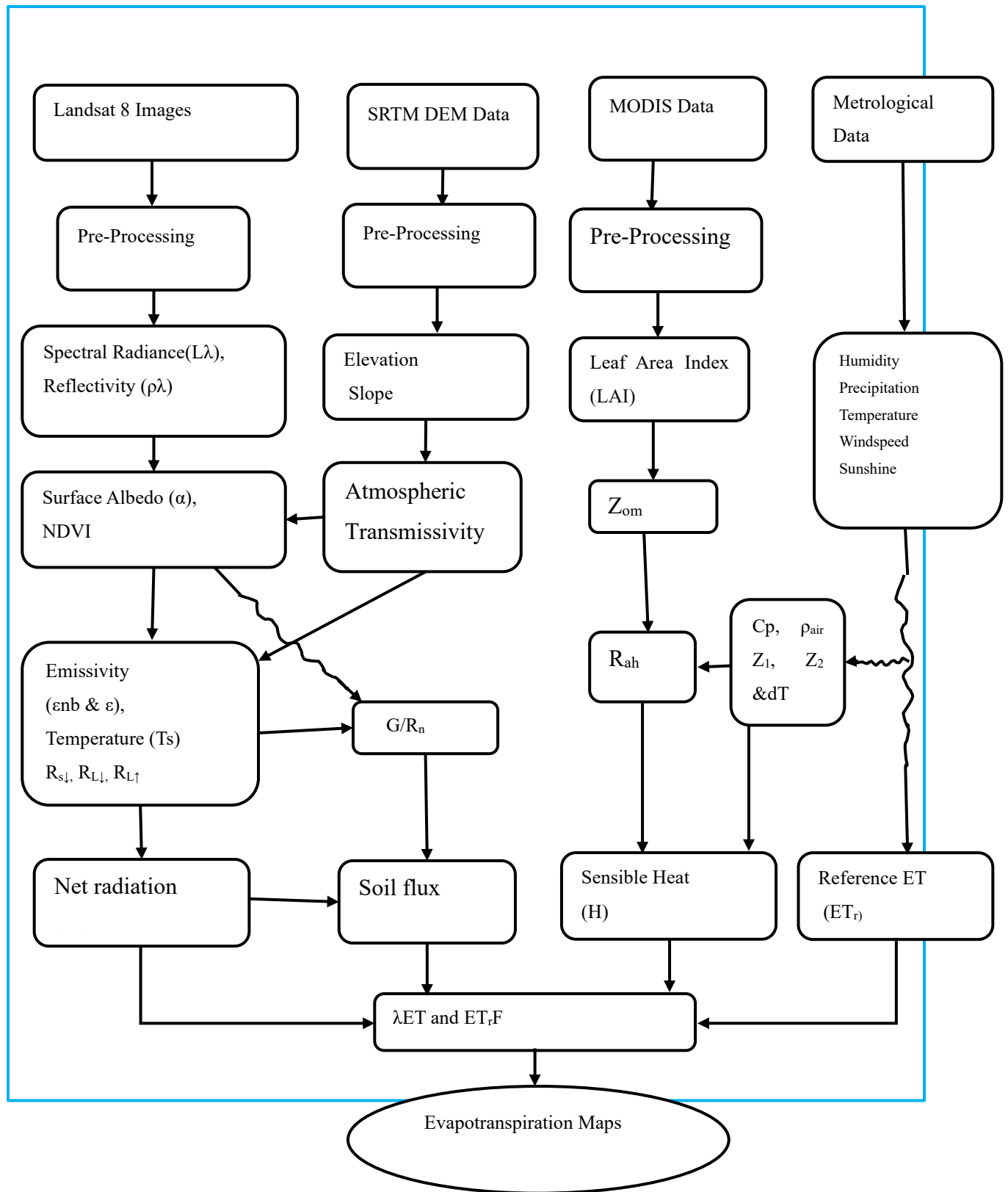


Figure 4. Methodological Flowchart of the Research Process for Estimation of Evapotranspiration (ET)

3. RESULTS: SPATIAL AND TEMPORAL DISTRIBUTION OF ET

3.1 Estimating Instantaneous Evapotranspiration (ET_{inst})

ET is latent heat flux (W/m), and λ Latent heat of vaporization (J/Kg) by (British et al., 2002). Across the four acquisition dates, the evapotranspiration rate was consistently higher in the forest area than in urban and agricultural land, so ET_{inst} is also higher in forest area than agricultural and urban area which is evident from results of all the dates. These values are instantaneous (ET_{inst}) extremes by land cover and are distinct from the daily ET₂₄ values reported by acquisition date in Section 3.1.1-3.1.4 and Table 2. As shown on the Figure 5, the study area had an instantaneous 8.239 mm/hr maximum value of instantaneous evapotranspiration (ET_{inst}) for forest and 0.482 mm/hr minimum value of ET_{inst} for the bare land. This pattern is consistent with the greater transpiration expected from denser vegetation cover, although a formal statistical correlation was not tested in this study.

3.1.1 ET Estimation for January 2020

The SEBAL model was applied to the Landsat-8 imagery acquired on January 12, 2020. The estimated instantaneous ET values were extrapolated to daily ET₂₄ values. The results showed a maximum ET₂₄ of 5.70 mm/day and a minimum ET₂₄ of 0.68 mm/day, with a mean value of 3.34 mm/day and a standard deviation of 1.12 mm/day. The spatial distribution map revealed distinct patterns correlated with land cover characteristics: areas with dense vegetation and irrigated agriculture exhibited the highest ET values, while bare soil, rocky outcrops, and sparsely vegetated areas showed the lowest ET values. The spatial pattern was also influenced by topography, with valley bottoms and riverine areas showing higher ET due to greater soil moisture availability and denser vegetation cover. The northern and eastern parts of the district, which are characterized by more rugged terrain and less vegetation cover, exhibited lower ET values compared to the western plains.

3.1.2 ET Estimation for February 2020

For February 8, 2020, the ET₂₄ estimates ranged from a minimum of 1.75 mm/day to a maximum of 8.08 mm/day, with a mean of 4.65 mm/day and a standard deviation of 1.43 mm/day. The overall ET values were higher than those observed in January, consistent with the progression toward the dry season peak temperatures. The spatial pattern continued to show strong correlation with land cover type, with irrigated agricultural plots and riparian vegetation showing the highest ET values. The spatial distribution indicated that the areas along the Tekeze River and its tributaries

maintained higher ET due to the availability of water for irrigation and the presence of denser riparian vegetation. The southern portion of the district, which has more extensive agricultural activity and access to surface water, exhibited higher average ET values compared to the northern highlands. The standard deviation of 1.43 mm/day indicated increased spatial heterogeneity, likely due to the increasing contrast between irrigated and non-irrigated areas as the dry season progresses.

3.1.3 ET Estimation for March 2020

The March 10, 2020 ET estimates showed a maximum ET₂₄ of 9.63 mm/day, a minimum of 1.43 mm/day, a mean of 5.42 mm/day, and a standard deviation of 1.62 mm/day. The March estimates represented the highest ET values across the four acquisition dates, reflecting the peak of the dry season with the highest temperatures and lowest relative humidity. The maximum ET value of 9.63 mm/day was observed in areas of dense irrigated agriculture and along the river systems where water was abundantly available. The minimum values were observed in areas of bare soil, rocky outcrops, and degraded land where vegetation cover was minimal. The increased spatial variability (standard deviation of 1.62 mm/day) reflected the growing water stress in non-irrigated areas, creating a sharp contrast between irrigated and rain-fed areas. The central and western portions of the district continued to show higher ET values due to the concentration of agricultural activity and access to irrigation water from the river systems.

3.1.4 ET Estimation for April 2020

For April 24, 2020, the ET₂₄ estimates ranged from a minimum of 3.15 mm/day to a maximum of 7.18 mm/day, with a mean of 5.15 mm/day and a standard deviation of 0.94 mm/day. The April values showed a slight decrease compared to March, which may reflect the onset of early rainfall events or reduced irrigation activity as farmers prepare for the upcoming rainy season. The maximum ET value of 7.18 mm/day was lower than the March peak but still substantial in areas with active irrigation. The standard deviation of 0.94 mm/day was the lowest among all four dates, indicating reduced spatial heterogeneity. This could be attributed to the beginning of soil moisture recharge from early rainfall, which partially homogenized the surface moisture conditions across the district. The mean ET value of 5.15 mm/day remained high, reflecting the continued dry conditions and high atmospheric evaporative demand.

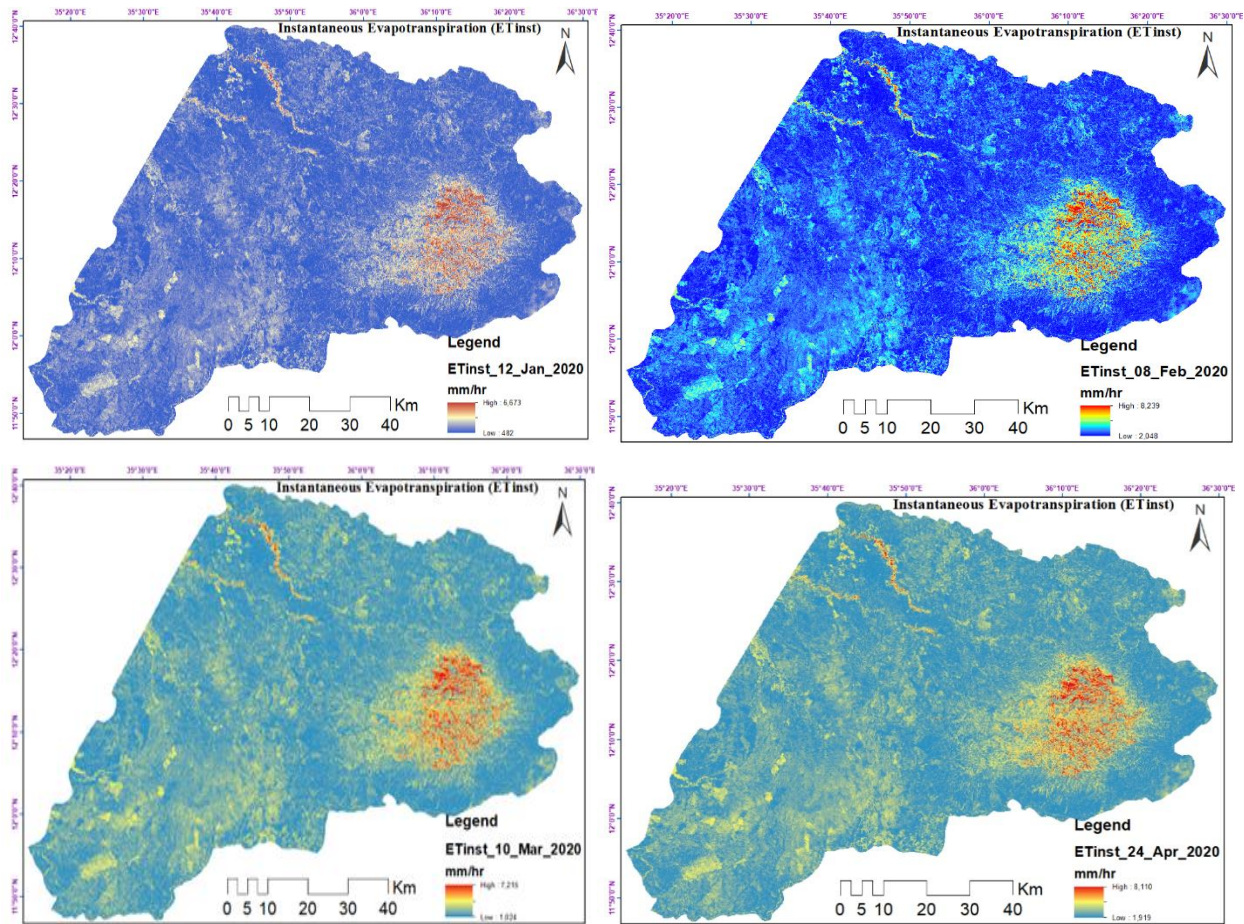


Figure 5. Instantaneous Evapotranspiration (ETinst) map of Quara District

3.2 Reference ET Fraction (ET_rF)

Reference ET Fraction (ET_rF) range from 0 to 1.4 and is assumed to be constant during the day depending on the self-preservation process in main surface energy balance components on the daily basis. At a totally dry pixel, $ET = 0$ and $ET_r F = 0$. A wet pixel with full vegetation cover can occasionally have an ET slightly greater than ET_r and therefore it may have a value of $ET_r F \geq 1$. However, ET_r generally represents an upper bound on ET for large expanses of well-watered vegetation. Since several assumptions were made for the computation of various variables, especially sensible heat flux, negative values can be expected.

The spatial distribution of ET_rF across Quara District is shown in Figure 6.

Reference ET Fraction (ET_rF) increases with increasing instantaneous evapotranspiration.

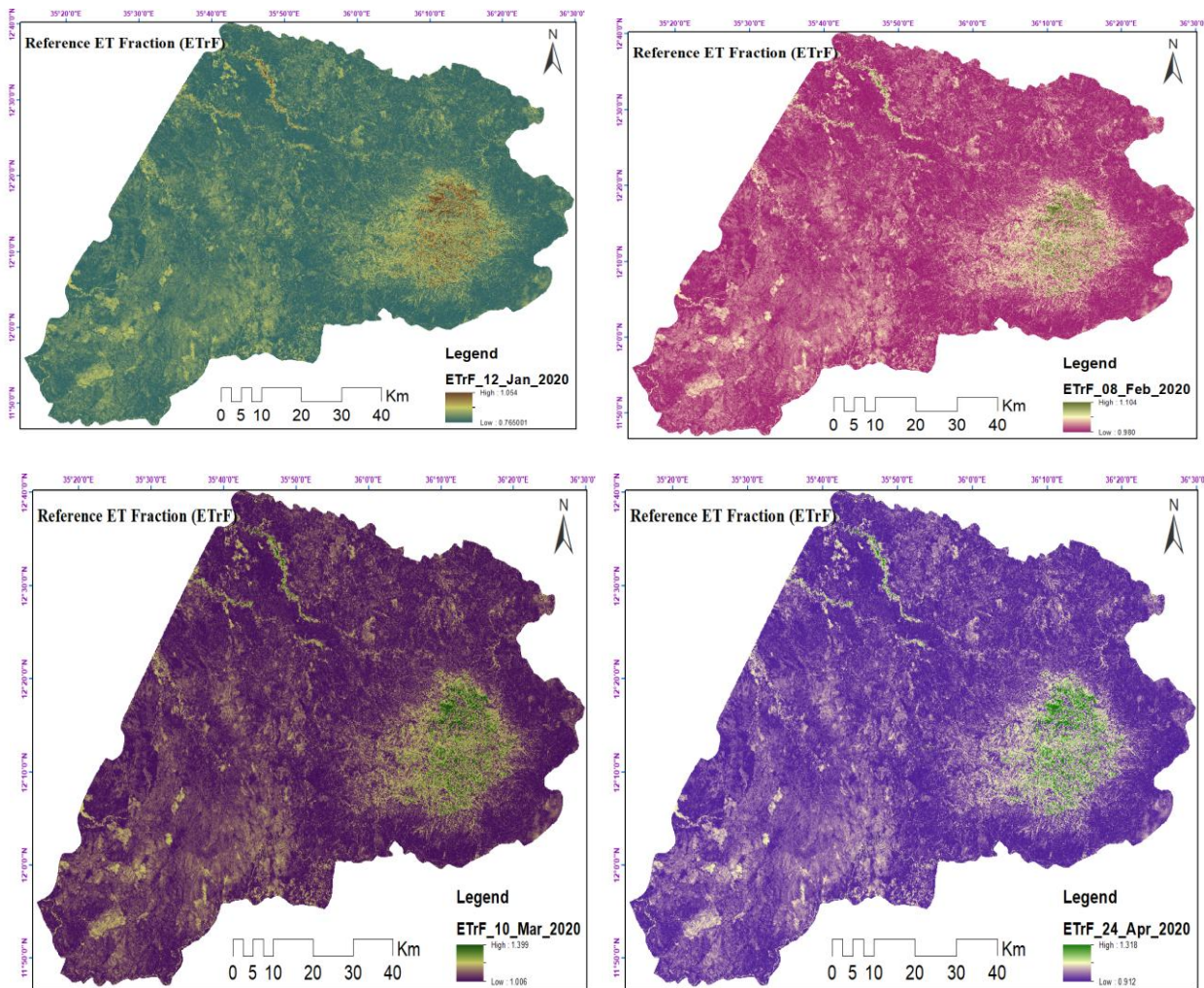


Figure 6. Reference ET Fraction (ET_rF) map of Quara District

3.3 Actual Daily Evapotranspiration (ET_{24})

Figure 7 shows the spatial distribution of actual daily evapotranspiration (ET_{24}) across the study area.

The process evapotranspiration establishes the link between water and energy balance and describe the land surface coupling with the atmosphere. The results show clear relation between land use/land cover and solar radiation parameters and impact of vegetation cover on the ET values in pixel wise domain. In the study, the main land use land cover class having high ET₂₄ value were forest and bare land, which covers 49 % of the study area and has the variation of ET₂₄ for different land cover shows the daily ET ranged from 3.655 mm per day at agricultural (crops) on February 08, 2020 to 9.630 mm per day at forest area. The main land covers controlling the ET characteristics is the forests, which is covering about 15% of the study area. The least range of variation in the daily ET values is appeared in the bare agricultural area which is characterized by the absence of vegetation cover during dry season. Factors that affect actual evapotranspiration include the plant's growth stage or level of maturity, its species, percentage of soil cover, soil type, solar radiation, humidity, temperature, and wind.

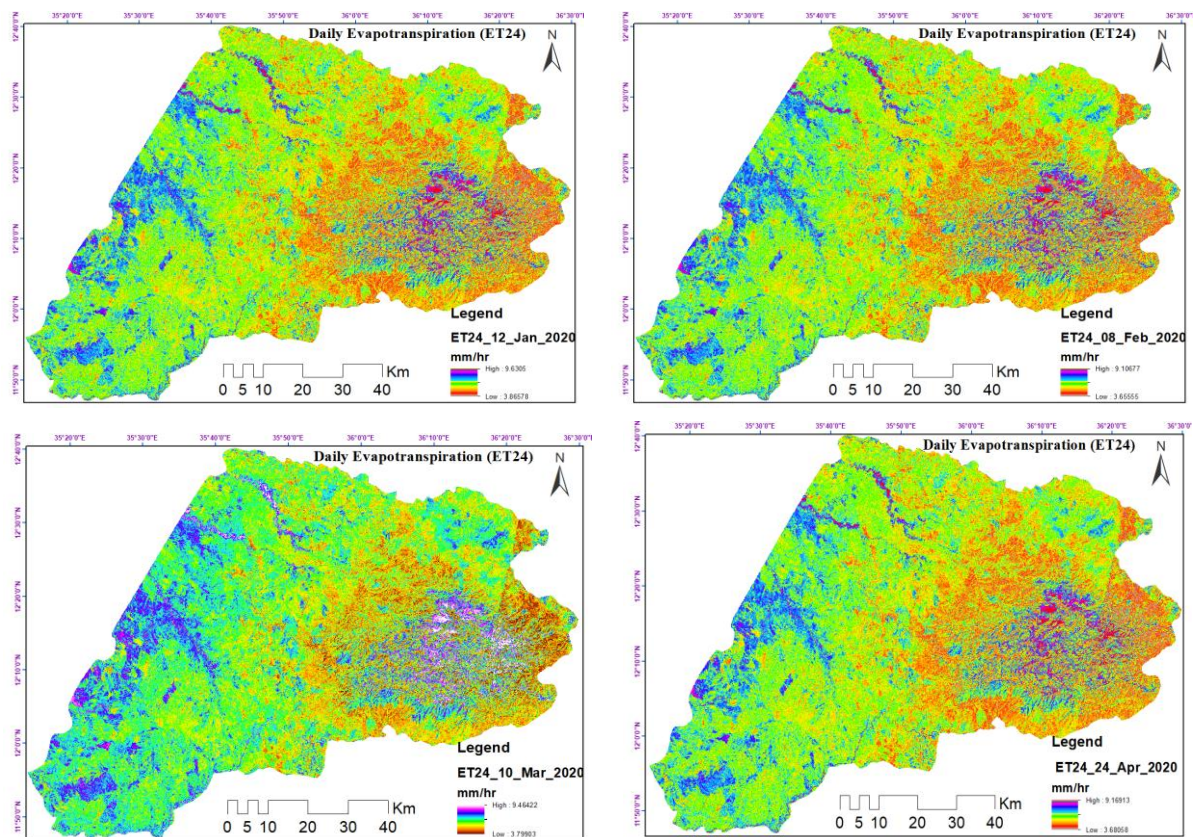


Figure 7. Actual Daily Evapotranspiration (ET₂₄)

3.2 Estimation of the Fluxes in the Surface Energy Balance

3.2.1 Net Radiation Flux (Rn)

Net radiation is the energy that makes the world habitable for humans, animals, and plants; it is also the energy that drives the earth's activity (Kundu, S. N, 2019). R_n can be positive, negative, or zero. It is positive when there is more incoming radiation than outgoing radiation which typically occurs during the daytime when the sun is out, and the air temperature is the warmest. At night, net radiation is usually negative as there is no incoming solar radiation and the outgoing terrestrial longwave flux dominates. Net radiation is zero when the incoming and outgoing components are in perfect balance, which does not occur too often. As shown in Figure 8, vegetation had high R_n 670.206 W/m^2 and bare land had low 124.996 W/m^2 comparing to other.

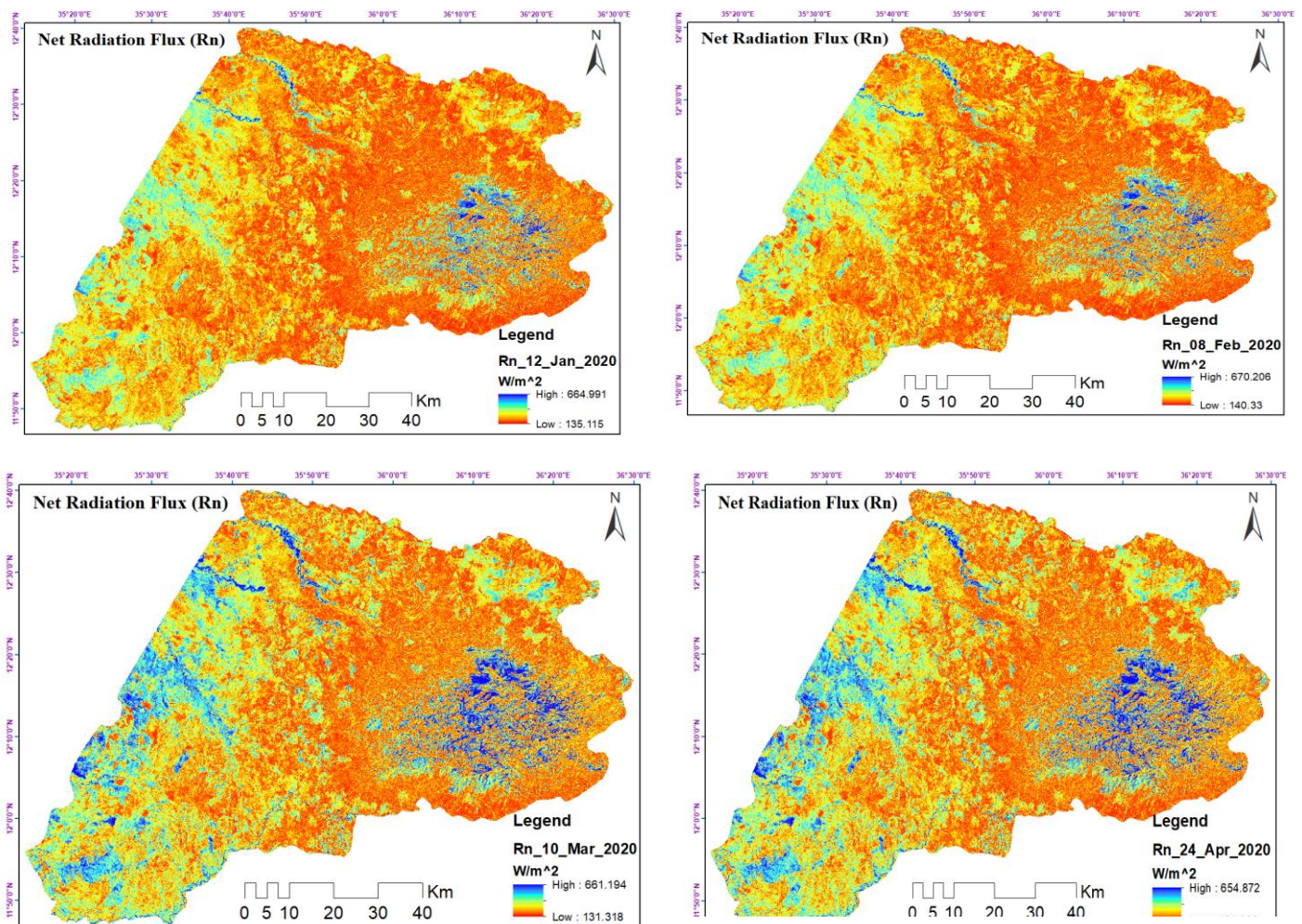


Figure 8. Net Radiation Flux (Rn) map of Quara District

3.2.2 Soil Heat Flux (G)

Soil Heat Flux (G) is the portion of the solar energy available at the surface that is absorbed or released by the soil in a given time (Bektaş Balçık et al., 2020). In remote sensing, it is not possible to measure the direct soil heat flux and it is indirectly calculated or explained as the derivation of soil heat using multiple functions such as surface albedo, Ts, and NDVI. Forest had a maximum value 196.91 W/m² on April 24, and crop land had minimum 45.268 W/m² on January 12, 2020. The spatial distribution of soil heat flux (G) is presented in Figure 9.

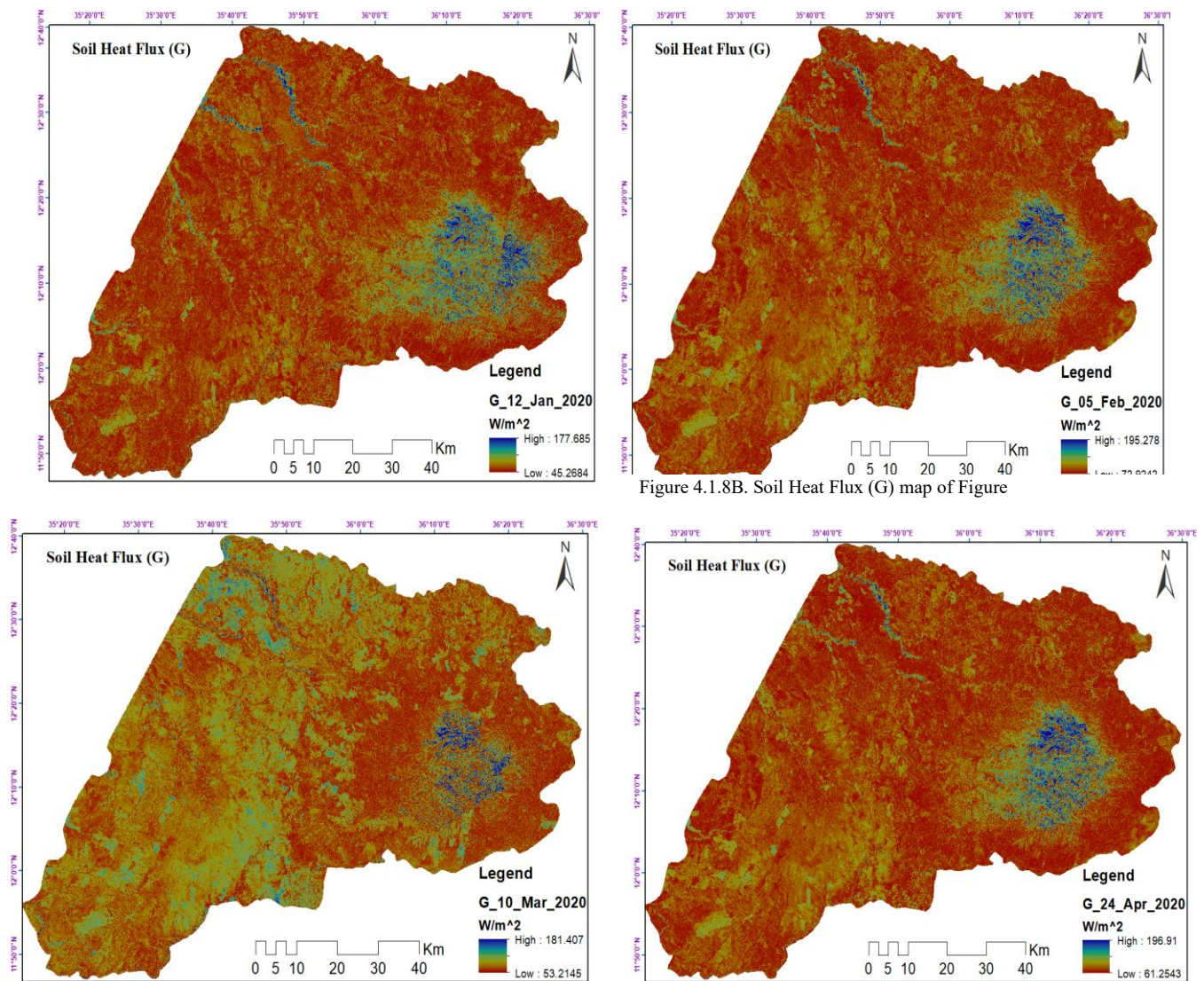


Figure 4.1.8B. Soil Heat Flux (G) map of Figure

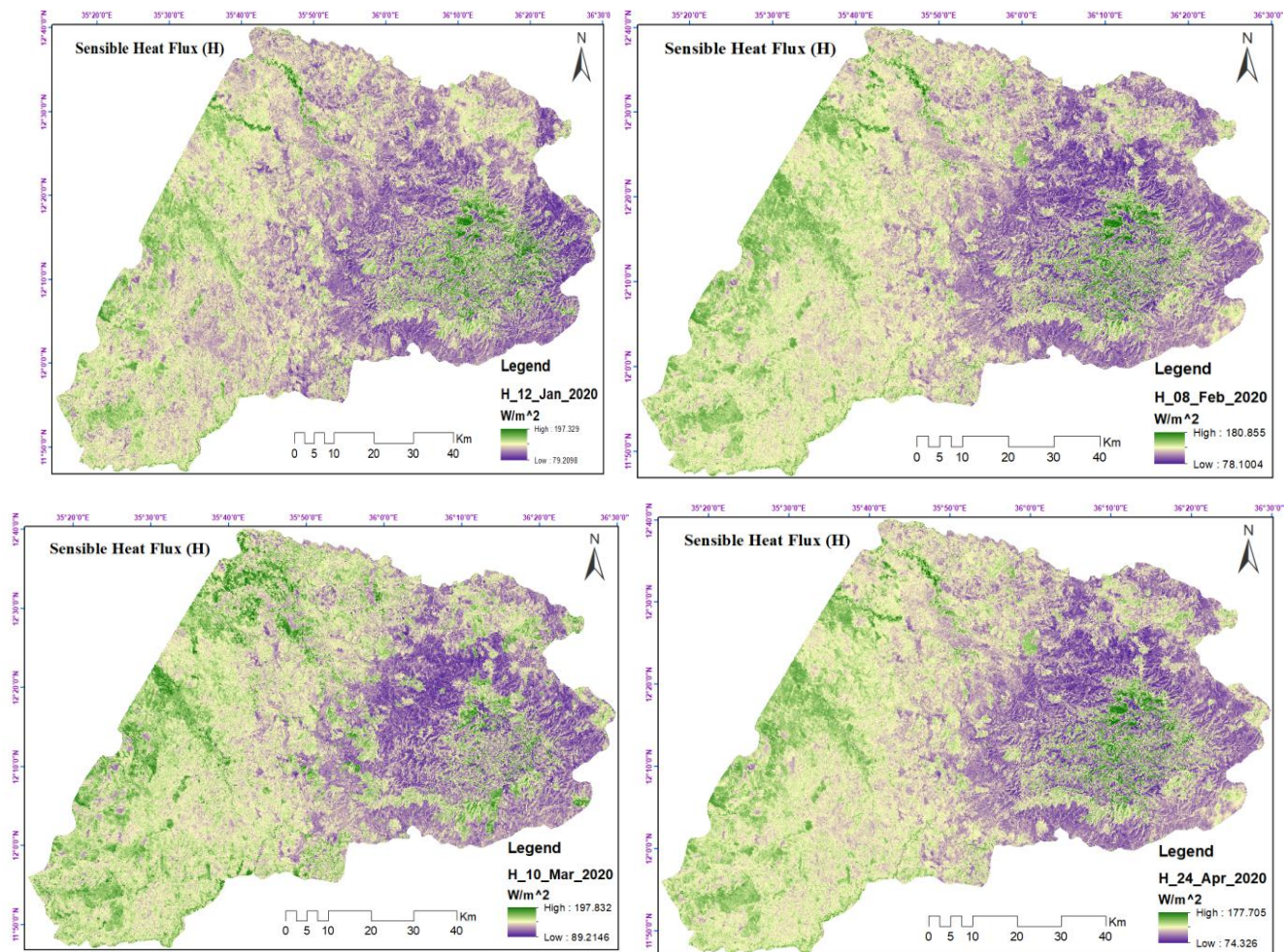
Figure 9. Soil Heat Flux (G) map of Quara District

3.2.3 Sensible Heat Flux (H)

This flux is extremely sensitive to factors like the dynamics of the turbulent heat transport system, natural landscape, and vegetation structure. Sensible heat flux is the rate of heat loss to the air by convection and conduction due to a temperature difference. Because the Leaf Area Index input was derived at a coarser resolution than the Landsat-8 bands, the resulting sensible heat flux map has a slightly coarser spatial texture than the other SEBAL outputs; however, this did not materially affect the final result of the actual ET map. The maximum of H was 197.832 W/m² for forest and a minimum of 74.326 W/m² of H for bare land.

Figure 10 illustrates the spatial distribution of sensible heat flux (H) across the study area.

Sensible heat flux was generally lower over more densely vegetated areas, on Sensible heat flux



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Figure 10. Sensible Heat Flux (H) map of Quara District

3.2.4 Latent Heat Flux (λET)

According to the soil water availability, vegetation type, rainfall, and latitudinal gradient, there is typically a daily as well as a seasonal variation in ET. In contrast, latent heat flux is the heat loss from the surface due to evapotranspiration without changes in temperature (Odai et al., 2021). As it was presented in Figure 11, the study area had approximately minimum λET values of -168.278 W/m^2 on March 10 for bare lands and maximum 415.355 W/m^2 on forests on January.

Latent heat flux, and by extension evapotranspiration, was generally higher over vegetated areas.

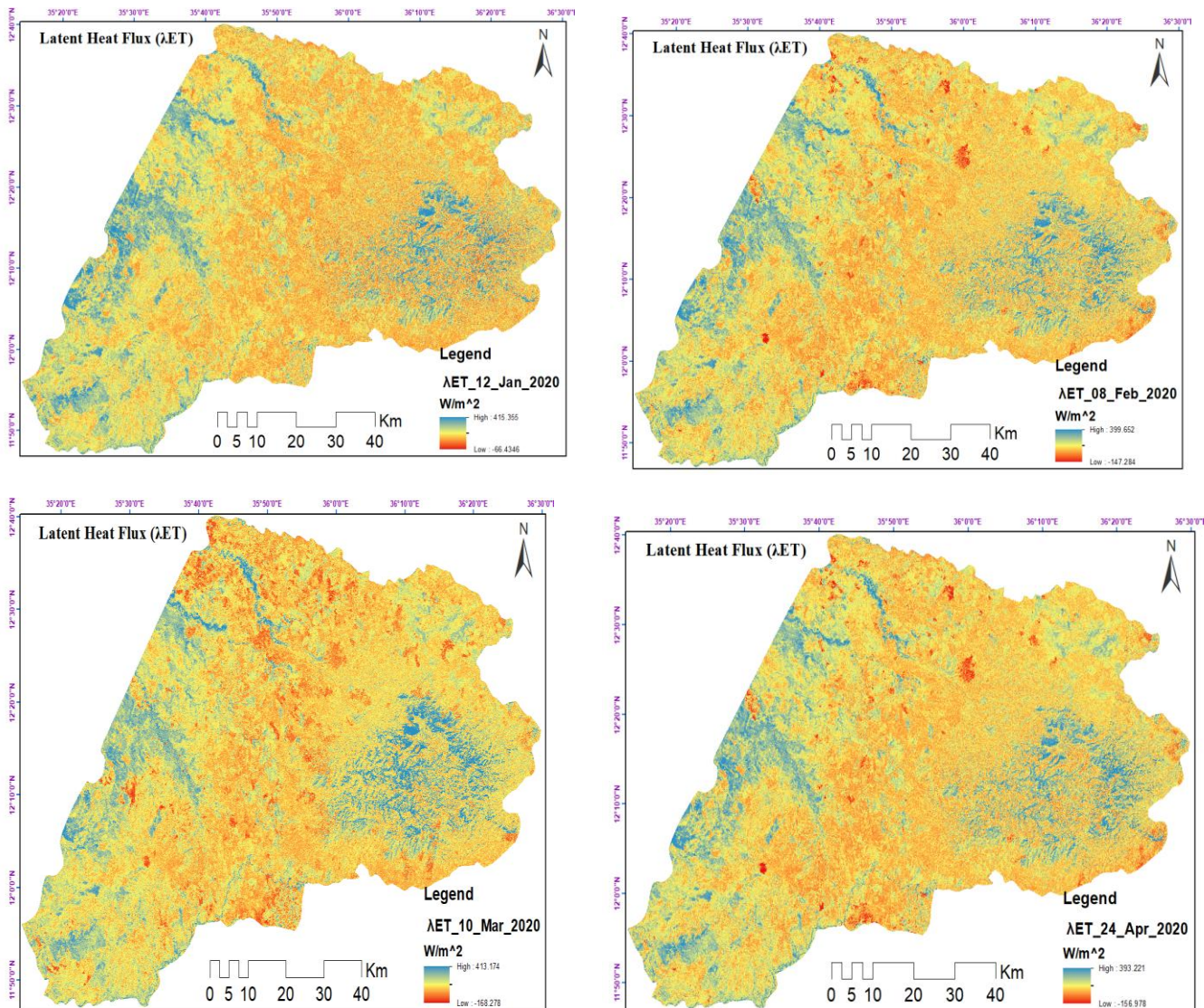


Figure 11. Latent Heat Flux (λET) map of Quara District

3.5 Summary of Temporal Variability

The temporal dynamics of ET across the four dry-season dates are summarized in Table 2.

Table 2. Summary statistics of estimated ET₂₄ (mm/day) for each Landsat-8 acquisition date.

Acquisition Date	Minimum (mm/day)	Maximum (mm/day)	Mean (mm/day)	Standard Deviation (mm/day)	Range (mm/day)
January 12, 2020	0.68	5.70	3.34	1.12	5.02
February 08, 2020	1.75	8.08	4.65	1.43	6.33
March 10, 2020	1.43	9.63	5.42	1.62	8.20
April 24, 2020	3.15	7.18	5.15	0.94	4.03

The temporal trend showed an increase from January to March, followed by a slight decrease in April. The overall temporal pattern can be explained by the following factors: (1) the progressive increase in atmospheric temperature and solar radiation from January to March, which increases the evaporative demand; (2) the depletion of soil moisture reserves in rain-fed areas, which reduces the available water for evapotranspiration; (3) the continued irrigation in areas with access to river water, which maintains high ET in irrigated plots despite the dry season conditions; and (4) the potential onset of early rainfall in April, which may recharge soil moisture and slightly reduce the contrast between irrigated and non-irrigated areas.

3.6 Spatial Pattern Analysis

The spatial distribution of ET showed strong coherence with land cover types and topographic settings across all four dates. High-ET zones were consistently associated with irrigated agriculture, riparian vegetation, and areas with high vegetation density. Low-ET zones were consistently associated with bare soil, rocky outcrops, sparse grassland, and degraded areas. The ET spatial patterns were also influenced by the topography: valley bottoms and riverine areas showed higher ET due to increased soil moisture and denser vegetation, while highland areas and steep slopes showed lower ET due to thinner soils and sparser vegetation cover. The spatial autocorrelation of ET values was significant, indicating that neighboring pixels tended to have similar ET values, which is consistent with the expected spatial continuity of land cover and soil moisture conditions.

4. DISCUSSION

4.1 SEBAL Performance and ET Magnitude

The ET values estimated by the SEBAL model in this study are comparable to those reported in similar studies using Landsat imagery in arid and semi-arid regions. For example, in their study in

the Gediz Basin of Turkey, Yilmaz et al. (2020) reported daily ET values ranging from 2 to 7 mm/day during the dry season using the METRIC model, which is conceptually similar to SEBAL. Similarly, in the Nile Delta, Bastiaanssen (2000) reported ET values ranging from 0 to 8 mm/day using SEBAL with Landsat-5 TM imagery. The maximum ET of 9.63 mm/day observed in March is within the range expected for irrigated areas in semi-arid regions with high solar radiation and temperatures. The minimum ET values approaching 0.7 mm/day are also consistent with completely dry bare soil surfaces where evaporation is severely limited by the absence of soil moisture.

The temporal trend observed in this study — increasing ET from January to March followed by a slight decrease in April — aligns with the expected seasonal pattern of evapotranspiration in semi-arid regions. The peak in March corresponds to the period of highest temperature and lowest humidity during the dry season, which maximizes atmospheric evaporative demand. The slight decrease in April may be attributed to the onset of early rainfall events, which increase atmospheric humidity and reduce the vapor pressure deficit, thereby moderating the evaporative demand. Additionally, some farmers may reduce irrigation activity in April in preparation for the rainy season planting, which could contribute to the observed decrease in ET.

4.2 Spatial Variability and Land Cover Influence

The strong spatial variability observed in the ET maps is consistent with the heterogeneous land cover composition of the Quara District. The district encompasses a mosaic of land cover types including agricultural fields (both rain-fed and irrigated), grassland, woodland, bare soil, and rocky outcrops. Each land cover type has distinct surface properties including albedo, surface roughness, emissivity, and soil moisture availability, which directly influence the partitioning of net radiation into latent and sensible heat fluxes. Irrigated agricultural areas consistently showed the highest ET values because they have high vegetation cover, adequate soil moisture, and high leaf area index, all of which promote transpiration. In contrast, bare soil and rocky areas showed the lowest ET values because they lack vegetation cover and have depleted soil moisture during the dry season.

The influence of topography on ET distribution was also evident, with valley bottoms and riverine areas showing higher ET than upland areas. This pattern is explained by the concentration of soil moisture in lower topographic positions, where runoff accumulates and subsurface water tables are closer to the surface. Additionally, valley bottoms often support denser vegetation due to

greater water availability, further enhancing ET. The topographic control on ET highlights the importance of incorporating DEM-derived variables in hydrological models for the study area.

4.3 Model Limitations and Uncertainty Sources

Several sources of uncertainty may affect the accuracy of SEBAL-derived ET estimates. First, the selection of anchor pixels (cold and hot pixels) is a critical step that influences the calibration of the sensible heat flux. The automatic selection algorithm may not always identify the most representative pixels, particularly in landscapes with high spatial heterogeneity. The presence of cloud shadows, haze, or aerosols can also affect the quality of anchor pixel identification. Second, the assumption of a linear relationship between dT and surface temperature is an approximation that may not hold perfectly for all surface types. Third, the assumption of a constant evaporative fraction over the diurnal cycle introduces some uncertainty in the extrapolation from instantaneous to daily ET, particularly under conditions of rapidly changing atmospheric conditions or when soil moisture is rapidly depleted during the day.

Additional uncertainties arise from the atmospheric correction process. The use of a single atmospheric transmissivity value for the entire scene may not account for spatial variations in atmospheric conditions, particularly in areas with complex topography or variable aerosol loading. The conversion from at-sensor brightness temperature to land surface temperature also involves uncertainty in the estimation of surface emissivity, particularly for mixed land cover pixels. The meteorological data used for validation were obtained from a single station (Bahir Dar) located approximately 150 km from the study area, which may not fully capture the local meteorological conditions over the Quara District. Despite these limitations, the validation results (reported in the companion validation study) showed a strong correlation between SEBAL ET and FAO Penman-Monteith ET, indicating that the model performed adequately for the study area.

4.4 Implications for Water Resources Management

The ET maps generated in this study provide valuable information for water resources management in the Quara District. The identification of high-ET areas can help prioritize water allocation for irrigation, particularly in areas with limited water resources. The quantification of water consumption by different land cover types provides a basis for estimating the total water demand in the district and for assessing the sustainability of current water use practices. The temporal evolution of ET during the dry season can inform drought monitoring and early warning systems, as areas with declining ET may indicate increasing water stress.

The integration of ET maps with other geospatial data such as land cover maps, soil maps, and groundwater data can support the development of integrated water resources management (IWRM) plans for the district. For example, areas with consistently high ET but limited access to surface water could be targeted for groundwater development or small-scale water harvesting interventions. The ET data can also be used to estimate the water balance of the district, providing a basis for understanding the relative contributions of precipitation, evapotranspiration, and runoff to the water cycle. Overall, the SEBAL-based ET estimation provides a cost-effective and scalable approach for monitoring water consumption in the Quara District, with potential for application across the broader Amhara region and other semi-arid areas of Ethiopia.

5. CONCLUSION

This study successfully applied the SEBAL model using Landsat-8 OLI/TIRS remote sensing imagery to estimate actual evapotranspiration in the Quara District, northwest Ethiopia, during the dry season of 2020. The key findings are:

- The SEBAL model produced spatially explicit ET maps that capture the spatial and temporal variability of evapotranspiration across the district. The ET values ranged from 0.68 to 9.63 mm/day, with a clear temporal trend of increasing values from January to March, followed by a slight decrease in April.
- The spatial distribution of ET was strongly correlated with land cover type, with irrigated agricultural areas and riparian vegetation showing the highest ET values, and bare soil and rocky outcrops showing the lowest values. Topographic position also influenced ET, with valley bottoms and riverine areas showing higher ET than upland areas.
- The temporal dynamics of ET during the dry season were driven by the progressive increase in atmospheric temperature and evaporative demand, the depletion of soil moisture in rain-fed areas, and the continued availability of irrigation water in areas with access to river systems.
- The SEBAL model demonstrated satisfactory performance for operational ET estimation in the Quara District when validated against FAO Penman-Monteith ET_r computed from a single meteorological station located approximately 150 km from the study area; this remains a viable alternative to ground-based methods for data-scarce environments, though the validation should be confirmed against denser in-situ networks in future work.

The study recommends the following for future research and application: (1) integrate multiple satellite sensors (e.g., Sentinel-2, MODIS) to increase temporal resolution for ET monitoring; (2) incorporate ground-based measurements (e.g., eddy covariance, lysimeters) for direct validation of SEBAL ET; (3) combine SEBAL with hydrological models to improve water balance estimates at the watershed scale; (4) extend the analysis to the wet season to capture the annual water cycle; and (5) apply the methodology to other districts in the Amhara region to support regional water resources planning. The integration of remote sensing-based ET estimation with GIS platforms provides a powerful tool for operational water management in arid and semi-arid regions of Ethiopia, supporting evidence-based decision-making for sustainable water use and agricultural planning.

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