# Remote Sensing-Based Estimation of Regional-Scale Evapotranspiration in the Lower Indus Basin

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## Abstract

Evapotranspiration (ET) is a key element of the terrestrial water cycle, significantly influencing the interconnectedness of global energy, water, and biogeochemical cycles. Mapping ET is vital for optimizing agricultural water management, estimating runoff, determining crop water needs, hydrological modeling, and conducting long-term water budgeting in various environments. These trends in ET and associated variables are important indicators of agricultural water usage and the responsiveness of water resources to each factor and changing climatic conditions. However, modeling ET and its spatio-temporal distribution across large areas remains challenging, hindering the understanding of ecosystem responses in the context of climate change. Over the past three decades, remote sensing-based tools for ET modeling have been widely used to manage water resources and enhance understanding of land-atmosphere interactions. This chapter analyzes one source energy balance model for estimating ET in the lower Indus basin, focusing on the Dera Ismail Khan District of Khyber Pakhtunkhwa. Landsat 8 OLI satellite imagery was utilized to obtain the energy flux at the pixel scale. The Indus River basin is a critical water source for Pakistan, supporting a major agricultural economy and supplying water for tens of millions people. Effective water management in this region is essential for meeting agricultural demands, supporting food security, and addressing challenges posed by climate change.

**Keywords:** Water Cycle, Evapotranspiration, Energy Balance, Landsat 8, Climate Change.

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## 1. Introduction

Water is fundamental to all life on Earth and is essential for creating a sustainable ecosystem (Syed et al., 2010; Trenberth et al., 2009; Vinukollu et al., 2011; Yang, 2015). It exists in various forms: liquid (such as rivers, lakes, and oceans), solid (like snow or ice), and gas (water vapor present in the atmosphere). However, with the growing global population and deteriorating water quality, the availability of clean and safe water is significantly declining worldwide. Oki and Kanae (2006) estimated that approximately 240 million people live in areas facing severe water scarcity. By 2050, two-thirds of the population will inhabit water-scarce cities, with nearly 46% of individuals potentially experiencing critical water shortages (Yang, 2015). Water in the atmosphere reaches the land surface through precipitation, with some of it flowing into rivers and contributing to runoff, while the remainder returns to the atmosphere through evapotranspiration. These processes are dynamic and vary across different spatiotemporal scales, forming the terrestrial hydrological cycle (Pan et al., 2008; Yang, 2015). Among all these processes, evapotranspiration is crucial for understanding global water balance and the interaction between the global water and energy cycles. Following precipitation, evapotranspiration constitutes the second-largest water flux in the terrestrial hydrological cycle, accounting for approximately 60% of the water that returns to the atmosphere from the Earth's surface (McMahon et al., 2013; Oki and Kanae, 2006; Trenberth et al., 2009). In semi-arid to arid regions, this proportion can exceed 90% (Bonan, 2015; Brutsaert, 2005). ET is a major component of the hydrological cycle, facilitating the exchange of energy and water among soil, vegetation, and the atmosphere (Ochoa-Sánchez et al., 2019). Three primary surfaces provide water for evapotranspiration: the ground, open water bodies, and plants. (Karanth, 1989).

## 2. Overview of Lower Indus Basin and Dera Ismail Khan (DIK)

The Lower Indus Basin, primarily located in southern Pakistan, is a crucial region for agriculture, economy, and ecology. The Indus River, along with its tributaries, plays a vital role in irrigation and water supply. The basin is characterized by a flat alluvial plain, supporting a diverse range of agricultural activities. A significant portion of the population in regions like DIK lives close to the river system because these areas offer essential resources for their livelihood. District DIK, located in the lower Indus basin of Pakistan (Fig. 1), has a climate that falls under the BWhw classification of the Köppen climate classification system. This classification is defined as a hot desert climate with dry winters (Sarfaraz et al., 2014). The winter season is mostly dry, whereas, the summer season is extremely hot, with average temperatures reaching 46 °C in June. This district is characterized by an arid alluvial plain known as "Damman" with silty sandy clay loam-type soil (Nasir and Ahmad, 2012). The North-Western boundaries are defined by the Khisor and Marwat mountains, as well as the Shaikh Budin hills (Ahmad et al., 2016). The River Indus plays a critical role in shaping the hydrological dynamics of DIK and influencing various aspects of the local water cycle. The scientific community utilizing remote sensing technologies to study the water cycle can significantly improve data monitoring and collection, offering a detailed perspective on hydrological changes over time. Additionally, grasping energy exchanges within the water cycle is crucial for forecasting rates of evaporation and their impacts on local climate, water availability, and agriculture in the study region.

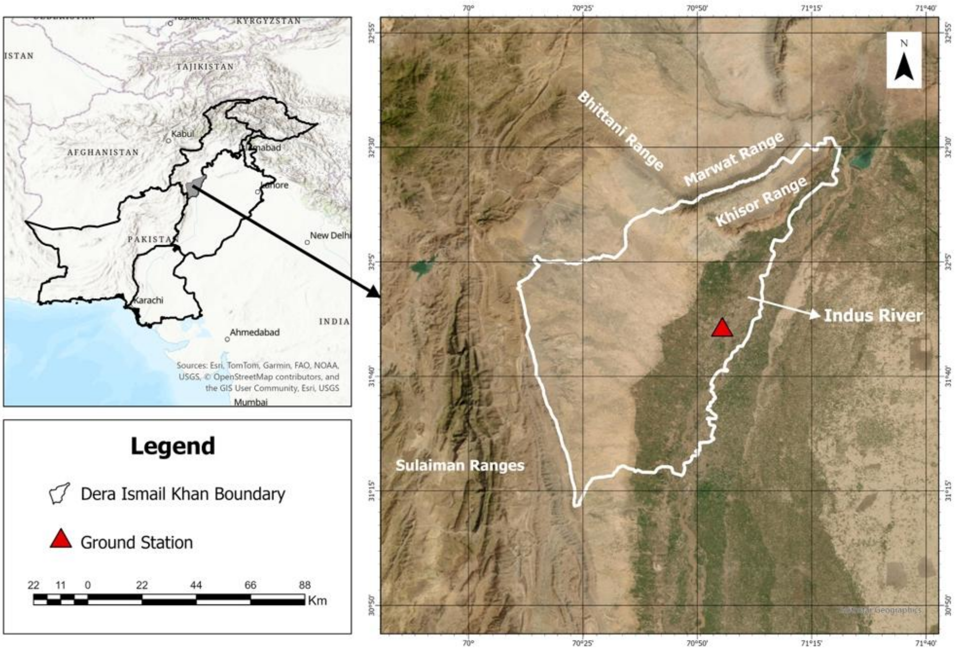


**Figure 1.** Location map of the Dera Ismail Khan district in southern Khyber Pakhtunkhwa.

## 3. Evapotranspiration (ET)

ET is the transfer of water from open surfaces such as, rivers, lakes, ponds, and soil through evaporation, as well as from vegetated surfaces via transpiration through stomatal openings (Fig. 2) (Allen et al., 1998a; Ghiat et al., 2021). ET consists of two main components, i.e., i) evaporation and ii) transpiration. Evaporation (E) is the process through which water is transferred from open water and soil surfaces to the atmosphere, while transpiration (T) involves the loss of water from aerial parts of the plants (Allen et al., 1998b). This process of transferring water to the atmosphere varies depending on surface conditions. Evaporation is a purely physical process, whereas transpiration is the physiological process of plants (Scott et al., 2006). ET influences energy and water balances, and these effects can be observed in various ecosystems. Zhang et al. (2021) noted that meadow degradation can lead to a significant decline in ecosystem productivity, impacting both water and energy budgets. Furthermore, evapotranspiration cools the land surface by reducing soil moisture content, which is why monitoring changes in land surface temperature (LST) or soil moisture using lysimeters is important for estimating ET. The rate of ET is influenced by several factors, including humidity, wind speed, sunshine duration, and sun elevation. It can vary significantly under different hydrometeorological conditions, with most water loss due to ET occurring during the summer months, while very little or none occurs in winter (DeVincentis et al., 2022; Fetter, 1994). Estimating evapotranspiration (ET) and understanding its spatiotemporal patterns are crucial for various fields related to the land surface processes, that includes surface hydrology, meteorology, hydrogeology, irrigation systems (Allen et al., 2007; Bos et al., 2008), water resource management, and agriculture (Biswas, 2004).

*Spatio-temporal Estimation of ET in Dera Ismail Khan*

Several methods and approaches are used to estimate evapotranspiration (ET) on a local scale. Among the well-known in situ techniques for measuring evapotranspiration are eddy covariance system (ECS) (Gutierrez et al., 2021; Markos and Radoglou, 2021), lysimeters (Doležal et al., 2018; Sarma and Bharadwaj, 2020), Bowen ratio method (Devitt et al., 1998; Prueger et al., 1997; Walls et al., 2020), and evaporation pans (usually Class A). Ground-based models can be classified into four categories: water balance models, micrometeorological models, soil-vegetation-atmosphere transfer models, and empirical models, with further details available in Yang (2015). While ground-based techniques provide detailed and precise measurements, their point-based nature due to small footprints limits their ability to represent large, spatially heterogeneous surfaces with varying hydrometeorological conditions (Wang et al., 2007). Nonetheless, these ground-based measurements can be valuable for validating spatiotemporal ET data products. To quantify ET and its spatiotemporal variability, multi-source remote sensing data, such as Landsat and MODIS satellite products, are widely utilized. Mapping spatial and temporal estimates of ET includes employing remote sensing techniques to monitor and measure the changes in ET and over time and surface moisture across different locations. Energy flux data from satellite products can be effectively used to estimate ET over extensive geographical areas on various temporal scales. Additionally, remote sensing methods are cost-effective and efficient for mapping spatiotemporal ET estimates.

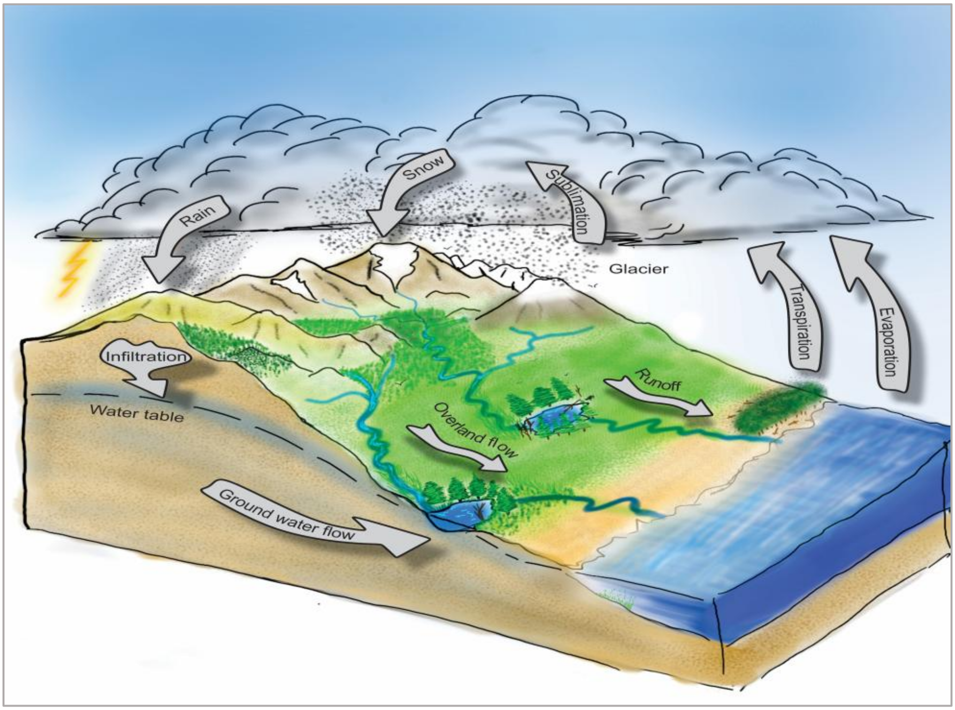


**Figure 2.** The Water Cycle (modified after Fetter, 1994).

## 4. Data and Methods

Two different types of datasets were used in this study i.e., meteorological data, and Satellite.

### *4.1. Satellite Data*

This study employed data from the Landsat 8 satellite, with an overpass time of approximately 10:00 AM ± 15 minutes, to analyze the spatial and temporal distribution of evapotranspiration (ET). The imagery was acquired from the United States Geological Survey (USGS) Earth Explorer, an open-access platform offering free satellite data. Specifically, images captured by the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) on Landsat 8 were used, as these sensors provide crucial information for analyzing land surface characteristics and temperature. To ensure the accuracy and reliability of the analysis, only images with less than 5% cloud cover were selected, minimizing interference from atmospheric conditions and enhancing the quality of ET estimations.

*4.2. Meteorological Data*

Ground-based data for this study was obtained from local meteorological stations operated by the National Agromet Centre in Islamabad. These observatories are equipped with Class "A" evaporation pans, which are standard tools used to measure evaporation rates. These pans allow researchers to determine the amount of water lost through evaporation by observing the change in water level over a specific period. The data collected from these stations is essential for validating satellite-based ET estimates and providing a reliable reference for understanding local evaporation dynamics.

*4.3. Energy Balance and Remote Sensing Approach (SEBAL Model)*

To apply the SEBAL model, this study used Landsat 8 OLI/TIRS imagery from 2017 to 2020 to calculate the Latent Heat Flux (LE) (Traversa et al., 2021) for each pixel in the images. SEBAL estimates the instantaneous LE flux for each pixel by computing it as a residual of the surface energy budget as illustrated in Fig. 3. This approach involves determining the difference between the incoming and outgoing energy fluxes at the Earth's surface, with the LE flux representing the energy used for evapotranspiration. The model's ability to estimate LE is critical for understanding water transfer and energy balance in the study area.

$$\lambda LE = R_n - G - H \tag{1}$$

$\lambda LE$ represents the Latent Heat Flux, Rn is the Net Radiation Flux, G refers to the Soil Heat Flux, and H denotes the Sensible Heat Flux. All of these fluxes are measured in energy units of $W/m^2$.

## 5. Results

The objective of this study was to assess the effectiveness of remote sensing and the energy balance method for estimating evapotranspiration in the lower part Indus River region and the district of DIK. ET is a complex process influenced by numerous factors, including wind speed, humidity, water content, sunshine duration, sun elevation, and surface albedo. Among these, surface albedo significantly impacts the energy balance system. The angle of incoming solar radiation greatly influences the response of reflected radiation, leading to variations in albedo that subsequently affect other SEBAL parameters, such as ground heat flux and ET rates. The sun angle varies with seasons and throughout the day, which in turn alters the albedo response (Kotoda, 1986; Ziar et al., 2019). Consequently, a sensitivity analysis is conducted for albedo (see Fig. 4 and Table 1) to evaluate its effects across different land uses, including snow, vegetation, built-up areas, and water.

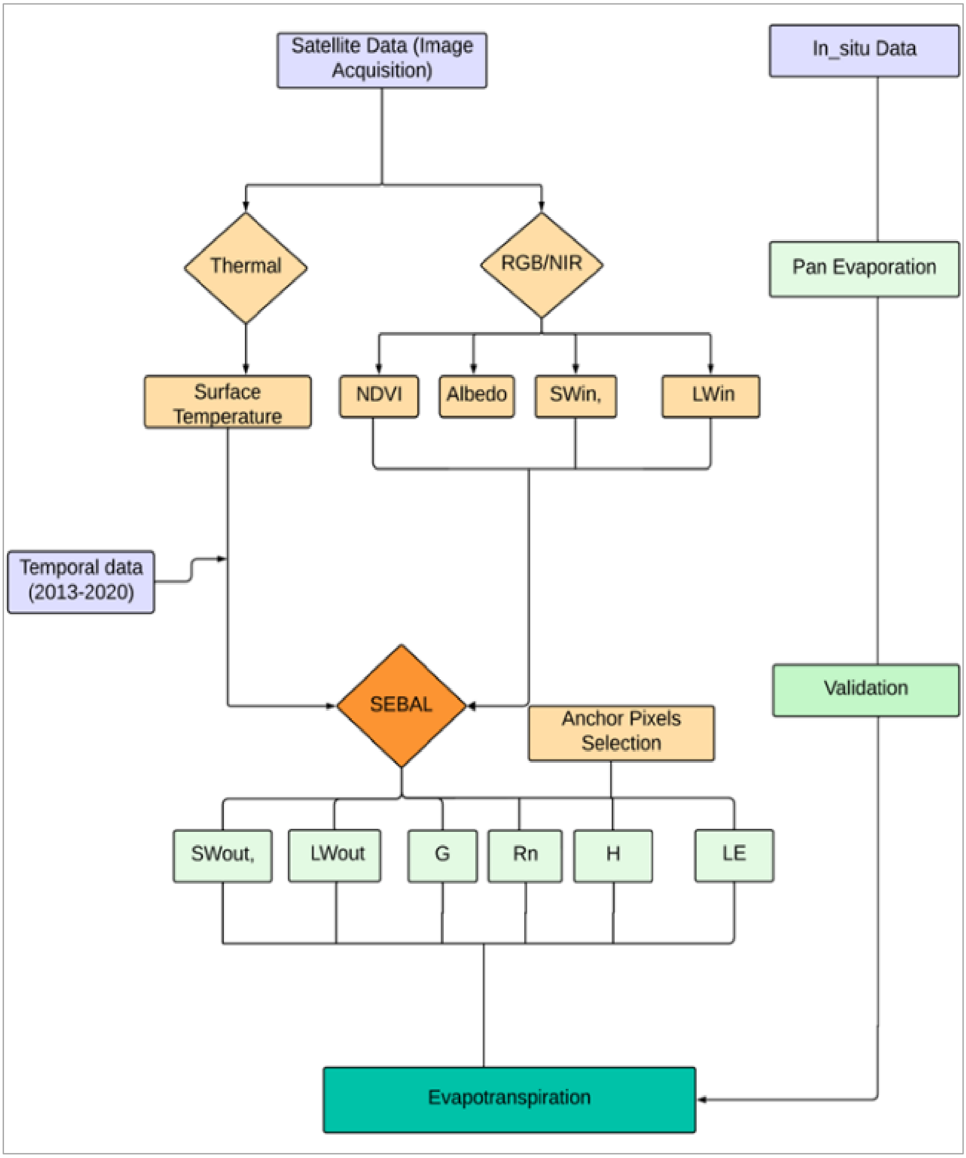


**Figure 3.** Flow chart of SEBAL model applied in the study.

**Table 1.** The albedo of different land cover types at various Sun elevations, with the values in parentheses indicating the standard albedo for each respective land cover category.

| Sun Elevation | Snow (0.9) | Vegetation (0.1-0.25) | Water (0.1-1) | Built-up (0.25-0.7) |
|---|---|---|---|---|
| 70 | 1.51 | 0.44 | 0.48 | 0.54 |
| 65 | 1.32 | 0.43 | 0.4 | 0.45 |
| 60 | 1.11 | 0.36 | 0.33 | 0.37 |
| 55 | 0.97 | 0.29 | 0.29 | 0.32 |
| 50 | 0.86 | 0.24 | 0.25 | 0.29 |
| 45 | 0.78 | 0.21 | 0.23 | 0.25 |
| 40 | 0.72 | 0.19 | 0.21 | 0.24 |

As shown in the results (Table 2 and Fig. 5) surface albedo, like sun elevation, is influenced by various surface characteristics. For example, the type and density of vegetation significantly affect albedo; dense forests typically exhibit lower albedo compared to grasslands and crops (Kotak et al., 2015). Green vegetation generally displays albedo ranging from 0.1 to 0.25 at angle of sun elevation ranges between 40º and 50º. Above 50º, albedo values exceed the standard range. Additionally, the albedo of soil is determined by soil type and moisture content, with highly saturated soils shows comparatively lower albedo and vice versa. Fresh snow can have a very high albedo, reaching values as high as 0.9 (Liu et al., 2015). Surface roughness is another factor that influences albedo. Different land covers respond differently at specific sun angles. For example, at a sun elevation of 55º, snow and vegetation show higher-than-standard albedo values (0.29 and 0.97, respectively), while water remains within the expected range at 0.29. As the albedo tends to increase with rising sun angle, this can lead to overestimations in albedo and, consequently, in energy fluxes. To mitigate this overestimation, lower sun elevation angles were utilized.

**Table 2.** Measured and estimated evapotranspiration (ET) values (mm/day) for D.I. Khan from 2017 to 2020, based on station data and SEBAL.

| Year | Station Based | SEBAL Based |
|---|---|---|
| 2017 | 4.11 | 4.31 |
| 2018 | 4.62 | 5.45 |
| 2019 | 5.00 | 5.90 |
| 2020 | 4.68 | 4.13 |

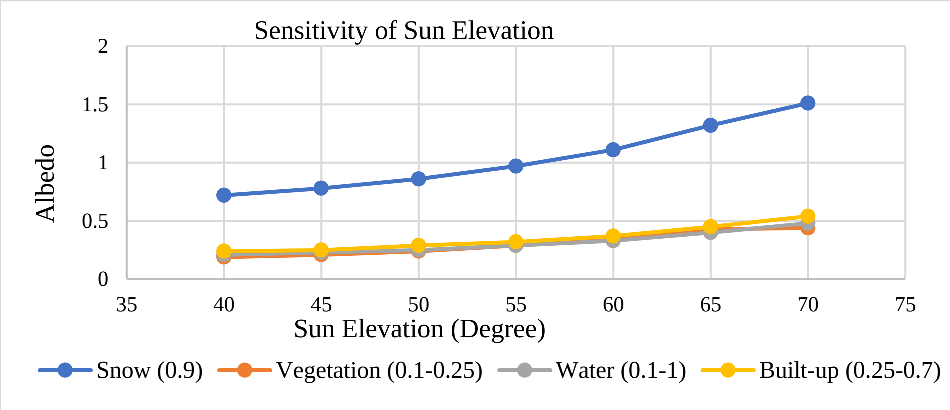


**Figure 4.** Scatter plot showing the Albedo of various land cover types.

In Fig. 4 and Table 2, the SEBAL-based maps present spatiotemporal estimates of evapotranspiration (ET) for the period from 2017 to 2020, covering the Indus River and DIK. This region features diverse topography, including mountain ranges in the northern and northwestern areas, while the Indus River flows to the east. The eastern part of the district shows the highest ET record and this increased ET is likely attributed to the river's presence, which provides significant moisture for evaporation and transpiration, thereby affecting the local hydrological cycle. The abundant vegetation along the riverbanks also plays a crucial role in enhancing transpiration rates, further contributing to the overall ET in the area. At the D.I. Khan test site, SEBAL-based ET ranged from 4.11 to 5.00 mm/day and 4.13 to 5.90 mm/day, respectively (Table 2.3). In 2019, the highest ET rates were recorded, with values of 5.0 mm/day (station) and 5.90 mm/day (SEBAL). Meteorological data indicated a rainfall event on June 4 and 5, 2019, with rainfall recorded by the meteorological station on June 5, 2019, prior to the satellite overpass time (10:00 AM ± 15 minutes). This rainfall might have contributed to the high ET values observed (station and SEBAL). In comparison, the lowest ET (4.11 mm/day) was recorded in 2017 for both the station and SEBAL estimates. The Indus River flows through the eastern and southeastern portions of the study area, potentially impacting ET rates in nearby vegetated and agricultural fields. In contrast, lower ET values are recorded in the northern and southwestern regions, likely attributed to the arid and barren characteristics of the mountain ranges in those areas. The dry conditions prevalent in these mountainous areas limit the capacity for significant water loss, reinforcing the idea that vegetation and water bodies are vital components in the regional water dynamics.

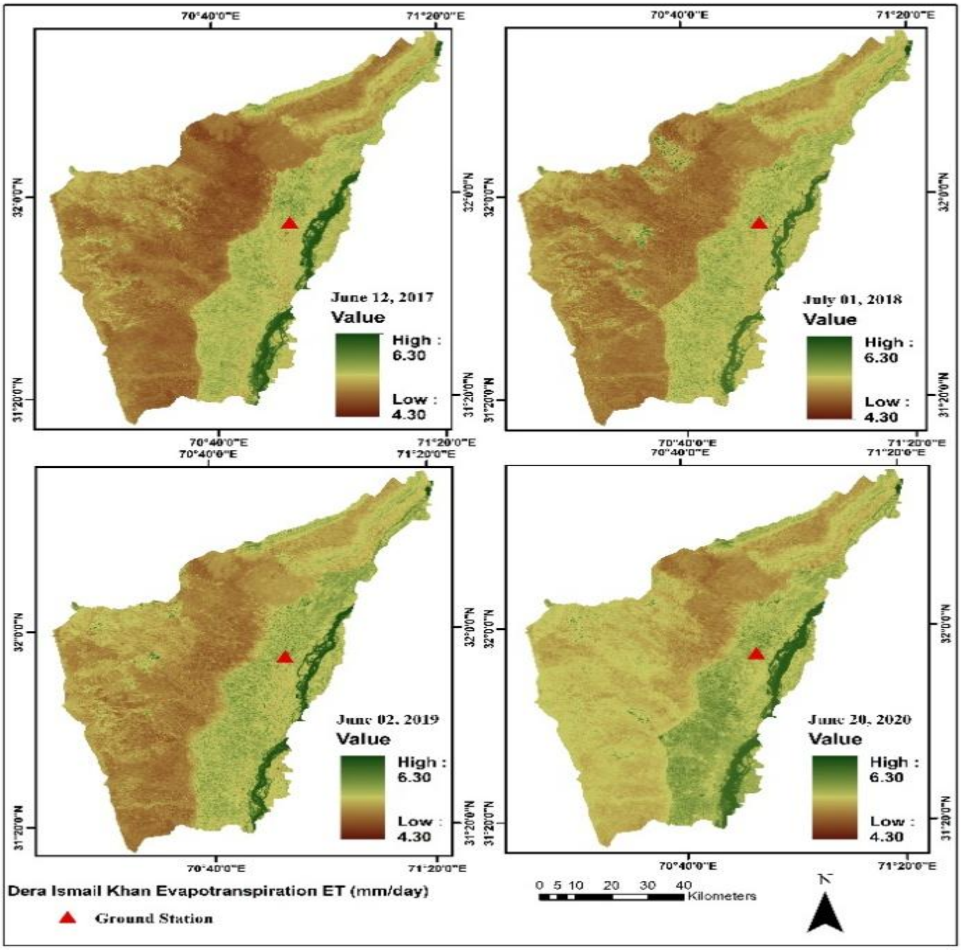


**Figure 5.** SEBAL-based evapotranspiration maps of Dera Ismail Khan.

The SEBAL model allows researchers to estimate ET using remote sensing data, which provides a comprehensive view of how water is being transferred from the land to the atmosphere across different landscapes. The maps indicate that regions near water bodies like the Indus River tend to have higher ET due to the moisture they provide. Vegetation plays a key role, as it not only absorbs water but also releases it back into the atmosphere through transpiration. In contrast, areas characterized by dry, barren land, such as the northern mountain ranges, exhibit lower ET rates because they lack the moisture and vegetation necessary to facilitate significant water loss through these processes. Overall, this analysis helps in understanding how various environmental factors influence water dynamics in the region. Climate change is expected to significantly alter precipitation patterns, temperature, and water availability across Pakistan. As temperatures rise, ET rates are likely to increase, intensifying water demands for agriculture. Monitoring ET can thus act as a sensitive indicator of how climate change impacts water resources, helping Pakistan prepare for potential shortfalls and adapt its agricultural practices.

Effective ET monitoring offers numerous benefits, such as:

I. Water Use Optimization: Through understanding crop water requirements by monitoring ET at different times of the year, the country can optimize irrigation, reducing water wastage and enhancing crop yield.

II. Improving Crop Water Productivity: With real-time ET data, farmers can manage water more effectively, aligning their practices with crop needs.

III. Adaptation to Climate Variability: Long-term monitoring of ET helps assess the impact of changing climate patterns on agriculture, providing insights for developing climate-resilient crops and water management strategies.

IV. Early Drought Detection: Monitoring ET anomalies can serve as an early warning system for droughts, helping mitigate impacts by implementing contingency plans.

## 6. Conclusion

The analysis of evapotranspiration (ET) estimates from the SEBAL model reveals significant insights into the hydrological dynamics of the Indus River region and DIK from 2013 to 2020. The findings indicate a clear correlation between proximity to the Indus River and high ET rates, highlighting the river's critical role in providing moisture essential for evaporation and transpiration. The lush vegetation along the riverbanks enhances these processes, thereby contributing to a more robust local hydrological cycle. In contrast, areas with arid and barren landscapes, particularly in the northern and southwestern regions, demonstrate markedly lower ET values. This disparity underscores the impact of land cover and moisture availability on ET rates. The dry conditions prevalent in these mountainous areas limit the capacity for significant water loss, reinforcing the idea that vegetation and water bodies are vital components in the regional water dynamics.

By employing remote sensing data through the SEBAL model, this study offers a comprehensive understanding of how various environmental factors, such as vegetation cover, land use, and proximity to water bodies, influence ET across diverse landscapes. The results not only contribute to the understanding of local hydrological processes but also emphasize the importance of managing these resources effectively in the context of climate change and increasing water demands.

Overall, this research provides valuable insights for policymakers and resource managers aimed at enhancing water resource management strategies, ensuring sustainable agricultural practices, and mitigating the effects of drought in the region.

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