Mapping Long-Term Trends in Actual Evapotranspiration in Data-Scarce conditions in Afghanistan

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Abstract: The agricultural sector in Afghanistan, the highest consumer of water resources, is crucial for food production and employment for over 50% of the population. As one of the top four most vulnerable countries to climate change, monitoring actual evapotranspiration (ETa) is imperative. However, conducting detailed investigations in countries facing data scarcity, like Afghanistan, remains challenging. Therefore, this study uses the TerraClimate dataset (4.6 km spatial resolution) to explore long-term ETa variation and trends in the Kabul River Basin (KRB). Integrating remote sensing data with advanced analytics, we examine the spatial and temporal dynamics of ETa in the Alingar watershed, a KRB subbasin. The results show that from 1980 to 2023, the mean annual ETa was 364±38mm. The Mann-Kendall test showed a significant trend (p-value < 0.05). This comprehensive investigation provides critical information for sustainable water management in Afghanistan.

Keywords: data-scarcity; TerraClimate; evapotranspiration; Kabul River Basin; Afghanistan.

1 Introduction

The agricultural sector in Afghanistan is the largest consumer of the country's water resources, playing a crucial role in ensuring food security and providing livelihoods for over half of the population. The country owns only 12% arable land (World Bank 2024) of which only 1.5–2.5 million ha are irrigated (Pervez et al. 2014). Despite the highest consumption (~98%) of the country's water resources (FAO 2019), the existing production does not meet the country's food demand. According to Akhtar et al. (2018), the supply-based irrigation system in Afghanistan is suffering from inefficiency in both conveyance and application. The conventional irrigation system has a water use efficiency (WUE) of 0.58 to 0.66 kg/m³. In the downstream of the Kabul River Basin (KRB), where laser land levelling has been implemented and the water supply is reliable, the highest application efficiency is 46% (Jalil et al. 2020). However, these interventions cover only a small fraction of the total irrigated area and are not representative of the entire country.

Given Afghanistan's ranking as one of the top four countries most vulnerable to climate change (DRMKC 2024), efficient water management is critical. Climate change may further affect water availability, potentially decreasing the current productivity of irrigated land. Therefore, regular monitoring of water resources is essential for understanding the water cycle, consumption patterns, and for developing sustainable agricultural practices and plans. However, Afghanistan faces the challenge physical data scarcity, which hampers detailed hydrological studies and effective water management strategies. Conventional ground-based data collection methods are often unrealistic in such regions due to logistical limitations and the infrastructure shortage. In this context, remote sensing and global datasets offer a valuable alternative, enabling researchers to monitor and analyse hydrological variables over large and inaccessible areas (Sagintayev et al. 2012). By integrating remote sensing data with advanced analytical methods, this study utilizes the TerraClimate dataset (Abatzoglou et al. 2018), which provides high-spatial resolution (4.6 km), to map long-term changes and trends in ETa within the Kabul River Basin (KRB), a region characterized by its heterogeneous landscape and different agro ecological conditions.

2 Materials and methods

2.1 Study Area

This study was conducted in the Alingar watershed (Figure 1), a subbasin of the Kabul River Basin (KRB) within the larger Indus Basin. The total area of this watershed is around 6,239 km². Its elevation varies between 601–5399 m above mean sea level. The mean annual precipitation received at this watershed during 2000–2019 was 634 mm. The forest coverage of this watershed is 31%, while rangeland including settlements and barren land covers around 64% of the total area; the water bodies are spread over 1% of the total area while 3% is the irrigated area in this watershed. The major rivers of this watershed are Alingar and Alishing.

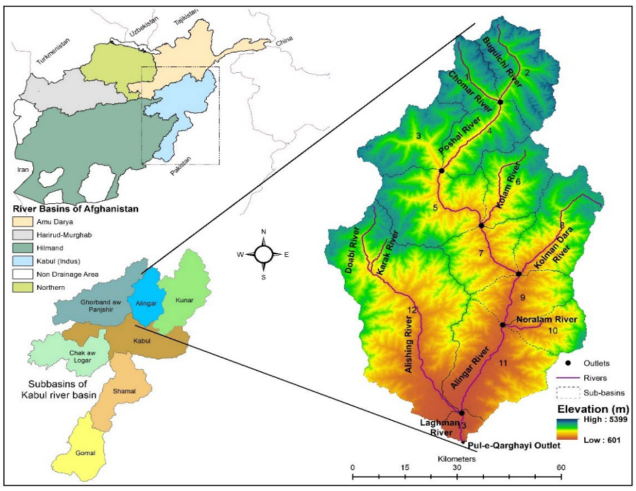

Figure 1. Geographic location and map of the Alingar watershed (Akhtar et al. 2022).

2.2 Data

In this study, we used the TerraClimate dataset, prepared by the University of Idaho, which provides monthly temporal resolution and climatic water balance information for terrestrial surfaces worldwide. It is based upon climatically aided interpolation and combines climatological normals derived from the WorldClim dataset. This product has a higher spatial resolution of 4.6 km, making it suitable for smaller scales studies in data-scarce regions. The TerraClimate data is available from 1. 1. 1958 to 31. 12. 2023, it contains fourteen bands, which are listed in Table 1.

Table 1. TerraClimate bands, University of Idaho (Abatzoglou et al. 2018).

Description	Min	Max	Units	Scale
Actual evapotranspiration (ET_a)	0	3140	mm	0.1
Climate water deficit (Def)	0	4548	mm	0.1
Palmer Drought Severity Index (PDSI)	−4317	3418		0.01
Reference evapotranspiration (PET)	0	4548	mm	0.1
Precipitation (Pr)	0	7245	mm	0
Runoff (Ro)	0	12560	mm	0
Soil moisture (SM)	0	8882	mm	0.1
Downward surface shortwave radiation (Srad)	0	5477	W/m^2	0.1
Snow water equivalent (SWE)	0	32767	mm	0
Minimum temperature (T_{min})	−770	387	^{0}C	0.1
Maximum temperature (T_{max})	−670	576	^{0}C	0.1
Vapor pressure (Vap)	0	14749	kPa	0.001
Vapor pressure deficit (Vpd)	0	1113	kPa	0.01
Wind-speed at 10m (WS)	0	2923	m/s	0.01

2.3 Estimation of actual evapotranspiration (ET_a)

As mentioned earlier, the TerraClimate has 14 bands, containing normal climate parameters to water balance components. We used Google Earth Engine to derive the ET_a covering a period of 1980–2023 by masking the study area.

2.4 Using Mann-Kendall Statistics test for Monotonic Trend in ET_a

For trend detection in the long-term ET_a estimations, we used Mann-Kendall (MK) test that provides the best alternative when the data is either positively or negatively skewed. The following equation (1) was used for MK statistics on monthly ET_a:

$$S_i = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i)\ \forall_i = 1 \ldots 12, \quad (1)$$

where n is the number of data points in the time series, x_i and x_j are data values at time i and time j respectively. The variance of S is given by equation (2):

$$VAR(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)}{18}, \quad (2)$$

where g is the number of tied groups in the data, t_p is the number of tied data values in the pth group. Once S and its variance are calculated, the following equation (3) test was performed to compute the standardized Z statistics:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & \text{if } S>0 \\ 0 & \text{if } S=0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & \text{if } S<0 \end{cases} \quad (3)$$

3 Results

3.1 Annual variation in mean actual evapotranspiration

The mean annual ET_a in the Alingar watershed during 1980–2023 was 364±38mm. The highest mean annual ET_a ever estimated during this period was 451 mm while the minimum ET_a was 287 mm. Figure 2 shows that the mean annual ET_a declined from 1996 until 2000. During this period, the country faced its most severe droughts on record, coinciding with internal conflicts among various warlords and their factions, resulting in substantial damage to irrigation infrastructure. With the establishment of a democratic government in 2001, initiatives targeting agriculture and irrigation were initiated. Consequently, a visible increase in ET_a is observed, reflecting the impacts of these interventions. From 2008, the mean annual ET_a consistently exceeds historical averages, indicating an increase in crop water consumption. This trend likely reflects a relatively stable water availability within the watershed during this period.

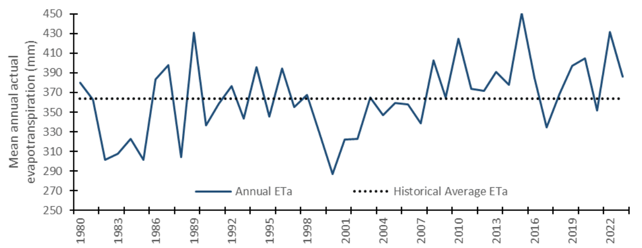

Figure 2. Variation in mean annual actual evapotranspiration (mm).

3.2 Inter-annual Variability in Monthly Mean Actual Evapotranspiration

Figure 3 given below shows that there is larger variation in the months of May-July, these are the months with highest crop water demand. These months overlap with higher temperatures and increase solar radiation that triggers the evapotranspiration rates. Specifically, in the month of May, the mean monthly ET_a was 80±13 mm, indicating a considerable amount of water required for crop growth during this time. The higher variation observed in May to

July can also be attributed to fluctuations in water availability, particularly in the form of excessive rainfall exceeding normal conditions in Spring and Monsoon seasons where precipitation amounts may vary adding more moisture to the crop root zone.

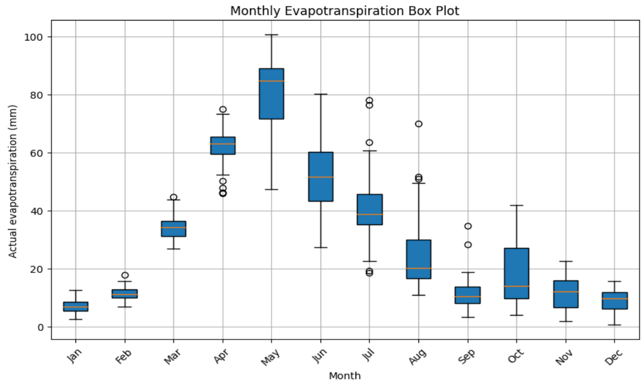

Figure 3. Inter-annual Variability in Monthly Mean Actual Evapotranspiration.

3.3 Trend Analysis

We used the Mann-Kendall non-parametric test (Mann 1945, Kendall 1975) to identify if the ET_a analysed for the study area follow any upward or downward trend. The summary of the results of the two-tailed MK test is given below in Figure 4.

The test results show a p-value of 0.002, which is less than the significance level (alpha) of 0.05 (Table 2). This indicates a statistically significant trend in the mean annual ET_a. The positive value of Kendall's tau (0.324) indicates the strength and direction of the trend, with positive values signifying an increasing trend. The slope value is 1.493, which is also positive and provides an estimate of the magnitude of the trend. A positive slope value confirms that the trend is increasing.

Table 2. Summary statistics of the two-tailed Mann-Kendall test.

Mann-Kendall trend test / Two-tailed test		**Sen's slope**			
Kendall's tau	0.324		Value	Lower bound (95%)	Upper bound (95%)
S	292	Slope	1.5	0.62	2.341
Var(S)	9129.3	Intercept	–2632.5	–4330.3	–877.06
p-value (Two-tailed)	0.002				
alpha	0.05				

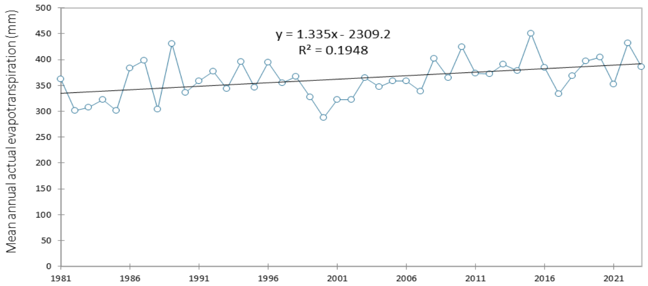

Figure 4. Trend analysis in the mean annual actual evapotranspiration.

4 Conclusions

The study of the Alingar watershed revealed that the mean annual ET_a from 1980 to 2023 was 364±38mm, with a range of 287mm to 451mm. A decline in mean annual ET_a from 1996 to 2000 corresponded with severe droughts and internal conflicts damaging irrigation infrastructure. Post-2001, agricultural and irrigation interventions led to an increase in ET_a, surpassing historical averages from 2008 onwards, indicating stable water availability and higher crop water consumption. The highest inter-annual variability in monthly ET_a occurred from May to July, reflecting variations in water availability. The Mann-Kendall trend test showed a significant positive trend in ET_a, with a p-value of 0.002, Kendall's tau of 0.324, and a Sen's slope of 1.49. The long-term analyses carried out by using the global datasets can help understand the hydrological and meteorological processes in the absence of physical datasets. Hence, it contributes to the planning and investment initiatives in the field of water resources management. However, the key limitation of using the global datasets for ET_a estimation is their spatial and temporal resolution, atmospheric interference and the need for validation against the ground-based measurements, which is difficult in data scarce situations.

5 References

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