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Assessment of Irrigation Performance in Large River Basins Under Data Scarce Environment - A Case of Kabul River Basin, Afghanistan

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Abstract

The Kabul River basin (KRB) of Afghanistan, a lifeline of around 10 million people, has multiplicity of governance, management and development related challenges leading to inequity, inadequacy and unreliability of irrigation water distribution. Prior to any uplifting intervention, there is a need to evaluate the performance of irrigation system on long term basis to identify the existing bottlenecks. Although there are several indicators used for the performance evaluation of the irrigation schemes, but we used the coefficient of variation (CV) of actual evapotranspiration (ET_a) in space (basin, sub-basin, and provincial level), relative evapotranspiration (RET) and temporal CV of RET to assess the equity, adequacy and reliability of water distribution respectively, from 2003 to 2013. The ET_a was estimated through surface energy balance system (SEBS) algorithm and the ET_a estimates were validated using advection aridity (AA) method with R^2 value of 0.81 and 0.77 at Nawabad and Sultanpur stations respectively. The global land data assimilation system (GLDAS) and moderate-resolution imaging spectroradiometer (MODIS) products were used as main inputs to the SEBS. Results show that mean seasonal sub-based RET values during summer (May – September) (0.37 ± 0.06) and winter (October – April) (0.40 ± 0.08) are below the target values (RET ≥0.75) during 2003-2013. The CV of mean ET_a within sub-basins and provinces for the entire study period has equitable distribution of water from October-January (0.09±0.04) whereas the highest inequity (0.24±0.08) in water distribution is during early summer. The range of the CV of mean ET_a (0.04-0.06) on monthly and seasonal basis shows the unreliability of water supplies in several provinces or sub-basins. The analysis of temporal CV of mean RET highlights unreliable water supplies across the entire basin. The maximum ET_a during the study period was estimated for Shamal sub-basin (552±43mm) while among provinces Kunar experienced the highest ET_a (544±39mm). This study highlights the dire need for interventions to improve the irrigation performance in time and space. The proposed methodology can be used as a framework for monitoring and implementing the water distribution plans in future.

Keywords: Data scarcity, actual evapotranspiration, surface energy balance, performance evaluation, Remote sensing

1. Introduction

The Kabul River Basin (KRB) is strategically very important for its transboundary nature and around 50% flow contribution to the overall outflow of the basin. Irrigated agriculture in the KRB depends mainly on water supplies from the Kabul River and its tributaries. However, there are severe flaws in water distribution systems which are causing around 40% of the total water loss due to poor operational performance [1]. Recent studies show that the climate variability/change will significantly impact the water flow patterns which will either cause

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severe droughts or otherwise heavy floods especially in irrigated areas of the KRB [2-4]. The predicted unreliable water supplies [5] coupled with poor performance of the irrigation system, would strongly impact the irrigated agriculture of the KRB and eventually the livelihoods of rural population.

The operational and strategic performance of irrigation systems requires continuous monitoring of associated set of irrigation performance indicators. There are different sets of indicators used for irrigation performance including relative evapotranspiration, delivery performance ratio, drainage ratio, depleted fraction, overall consumed ratio, field application ratio, annual relative irrigation supply, annual relative water supply, conveyance ratio etc [6]. These indicators are used to assess the equity, adequacy and reliability of the water distribution. Some of these indicators need field data (e.g., field application ratio) whereas others can be assessed by remote sensing without relying totally on ground field measurements (e.g., relative evapotranspiration). Moreover, some of the indicators are used to assess the performance at system level whereas others are used to assess the performance at field level. Due to unrest, insecurity and under-developed institutions, it is difficult to get the secondary and primary data in the KRB required for assessing the irrigation performance. However, recent developments in remote sensing make it possible to assess the irrigation performance at system level without total reliance on ground data.

The equity, reliability and adequacy are the main challenges in water distribution at system level for water managers not only in the KRB but also in other large irrigation schemes around the world [7, 8]. In the current study, we assessed the equity, reliability and adequacy of KRB at system level (e.g., provinces and sub-basin scale). We used the metrics which requires only remote sensing data and have been documented well in other studies. For example, RET was used to assess the adequacy of water distribution at water user's association level by using satellite remote sensing [8, 9]. Similarly, [10], [11] and [7] used the CV of actual evapotranspiration (ET_a) for assessing equity, the seasonal evaporative fraction for assessing adequacy and temporal CV of evaporative fraction for describing reliability. Thus, the objective of the current study is to assess the irrigation performance of the data-scarce KRB through a set of criteria (equity, adequacy and reliability) across the constituent sub-basins and provinces of the KRB for a period of 2003 - 2013. The coefficient of variation (CV) of mean ET_a, RET and CV of RET were the metrics to assess the equity, adequacy and reliability, respectively. This study not only provide guidelines for the water managers in the region to optimize the operational and strategical performance of the KRB but also the proposed set of indicators can be used as part of monitoring and evaluation criteria for irrigation performance by the relevant platforms in the future. The proposed set of indicators could also be helpful for the performance evaluation of the irrigations systems in data-scarce basins where ground-based measurements are missing or otherwise difficult to perform.

2. Materials and Methods

2.1. Description of the study site

The Kabul River Basin (KRB) is one of the five major river basins of Afghanistan having around 72, 646 km^2 of land area. It spans a wide swath of land starting from the central highlands of the country at 6, 000 m above mean sea level down to the valleys in the east at 400 m above mean sea level (Figure 1).

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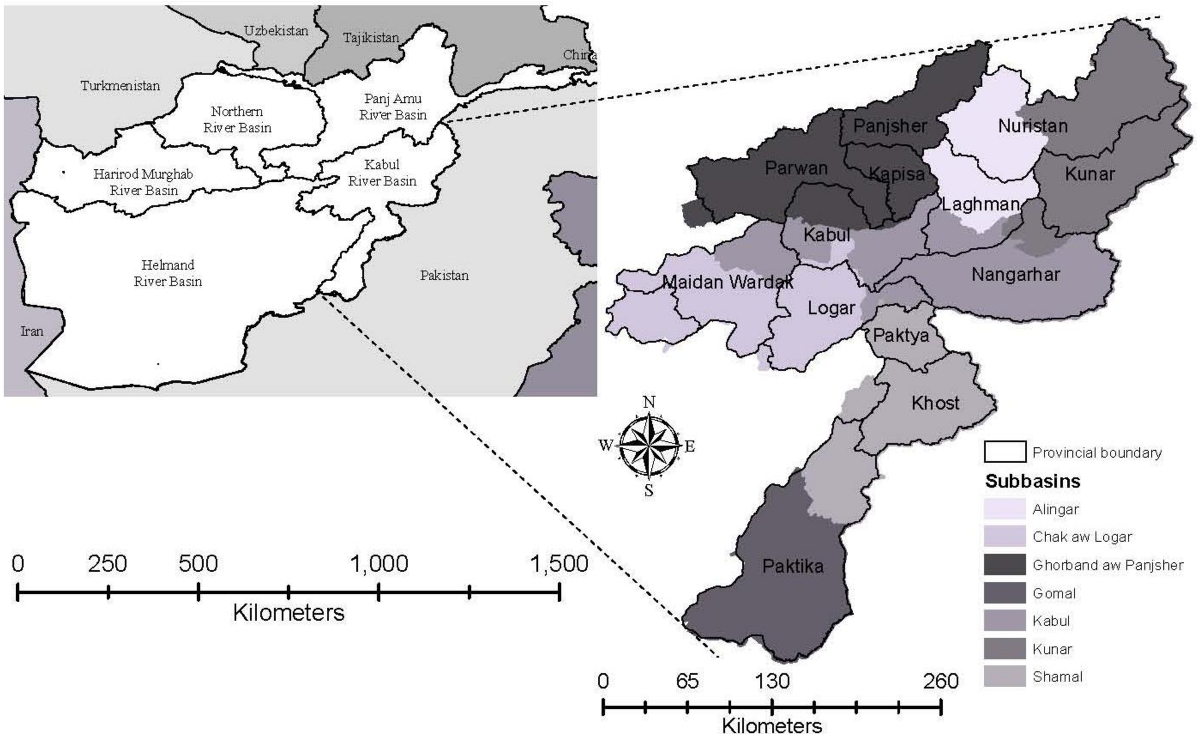

Figure 1: Location of the Kabul River Basin with its sub-basins and provincial

In 2013, the KRB received an annual precipitation of 327 mm at the downstream with a usual fringe effect of the Indian monsoon coming from the South Asian Himalayas as well as around 418 mm at the upstream. The mean annual temperature at the central upstream and downstream location were 13^{0}C and 23 ^{0}C, respectively (Figure 2).

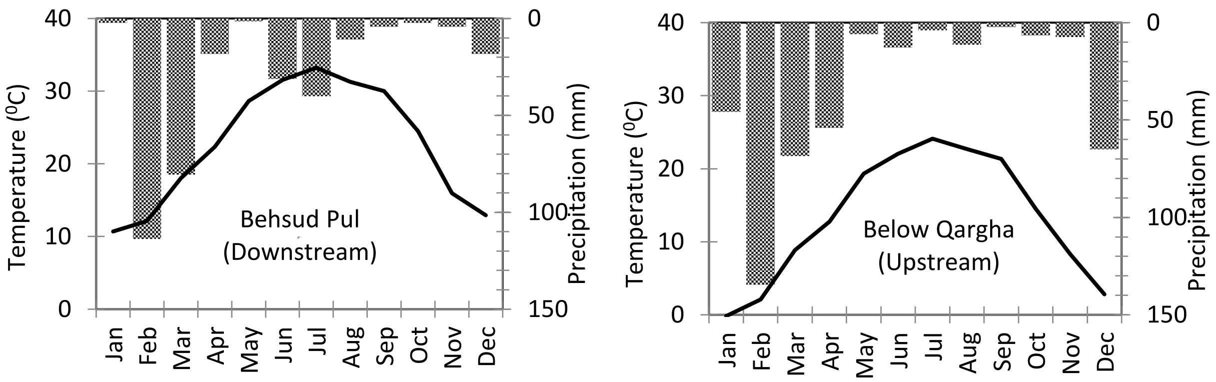

Figure 2: Climatograph of the downstream (left) and the central upstream (right) of the Kabul River Basin

Around 9% of the total land area of the KRB is cropland [12] . The main sources of irrigation of the cropland in the KRB are canals, streams, springs, *karezes* (underground water channels which exploit unconfined aquifers in alluvial fans which are recharged by snowmelt) as well as groundwater wells. Due to the relatively intensive conventional canal networks developed in the eastern provinces mainly Nangarhar, Laghman and Kunar, irrigated agriculture contributes the most to the food production in the KRB. There is an additional potential for the enhancement of irrigated agriculture [13] provided with modifications in the irrigation infrastructure and economical investment [14]. The existing irrigation system in the KRB is made of conventional schemes usually developed, constructed, operated and maintained by

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farmers according to the traditional customs and practices with some exceptions of recent interventions by the Afghan government. Most of the farmers are unaware of the actual crop water requirements and scheduled irrigations for the crops that are being grown locally. As a consequence, the delivery of water to field is based on the rule of maximizing the amount captured, leading to imbalance and water losses at different reaches along the canals with potential yield and biomass loss.

2.2. Diagnosis of the irrigation system performance of the KRB

For the diagnosis of the irrigation system performance, researchers use different indicators ranging from overall consumed ratio [15], crop water deficit [16], relative water supply [17], relative evapotranspiration [7, 8], delivery performance ratio, drainage ratio and depleted fraction [8] and equity and reliability [7, 11] etc. For this study, equity, adequacy and reliability were used as the prime criteria for assessment of the irrigation performance at administratively important spatial units (sub-basin, and provincial) and strategically viable time steps (Annual, monthly and seasonal). The choice of these indicators is mainly due to its requirement of the mainly remote sensing based ET_a data rather than detailed secondary data or field measurements which were hindered by the prevailed insecurity and political instability in the rural irrigated regions of the KRB. Moreover, the selection is also based on the consideration of quantifiability, cost effectiveness and accuracy required [18].

Equity is an extremely important aspect of irrigation management which deals with spatial distribution of water from the system manager's point of view for large supply based irrigation systems [19]. But in areas like KRB, suffering from multilateral issues (e.g. infrastructure damage, poor hydro-meterological network and water scarcity, etc.), equity in water consumption is more relevant at system level and therefore can be computed from the remote sensing based estimates of ET_a. The CV of ET_a was used as the key indicator to assess this criterion across the sub-basins and provinces both in summer and winter seasons from 2003 to 2013. The CV used here is a measure of the relative variability which was calculated as the ratio of the standard deviation of the mean monthly ET_a (2003-2013) to the mean monthly ET_a (Equation 1):

$$CV = \frac{Standard\ Deviation\ (\sigma)}{Mean\ (\mu)} \qquad \text{Equation 1}$$

The high CV of ET_a across the spatial constituent units of the KRB (i.e. sub-basins and provinces) would reveal high inequity in the irrigation system and vice versa. *Adequacy* is used to assess the reduction in ET_a as well as to evaluate the sufficiency of water delivery to a known command area [17]. For the evaluation of the adequacy, the relative evapotranspiration (RET) was used to detect the areas with water shortages over a time span of 2003 - 2013. The RET is very important in relation to monitoring of agricultural drought as well as crop yield forecasting. Relative evapotranspiration is known to be a reliable measure of plant available soil water and is proportional to plant growth [20]. The RET was calculated as a ratio of ET_a to ET_c as given in Equation 2.

$$RET = \frac{ET_a}{ET_c} \qquad \text{Equation 2}$$

The higher values of RET in a specific sub-basin shows that this sub-basin is under lesser stress and vice versa. Usually $RET \geq 0.75$ is acceptable for irrigated agriculture although it is

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constant over time [21, 22]; while RET between 0.75 and 1.0 shows adequate water supply [8]. The value of RET=0.65 is considered to be the critical value [23] and below that level (RET<0.65) is considered be poor performance of the irrigation system and eventually the loss to the crop yield and biomass. *Reliability* is the measure which describes the sufficiency of water availability for crops' consumption throughout the season. Therefore, the temporal CV of RET across the constituent provinces of the KRB was used for the assessment of the water reliability.

2.3. Actual evapotranspiration estimated by remote sensing

There are different algorithms for mapping the ET_a but their selection depends on the level of accuracy required, geographical conditions of the targeted area and model limitations etc. [24]. Based on the acceptable estimates of the Surface Energy Balance System (SEBS) algorithm [25] used at the Indus Basin [26] and similar regions [27, 28], it was also chosen for this study to estimate ET_a for the KRB. The GLDAS and MODIS data were used as inputs to the SEBS. Furthermore, it is a well-established model and has been validated under different agro-climatic conditions of the world. Former studies show that SEBS results when validated against observed eddy covariance (EC) technique [29], ground-measured ET_a [30] and ET_a estimated with advection aridity (AA) in the Indus Basin [26] yielded an acceptable correlation. In this study, we used AA method due to its least ground data requirement, high reliability and successful implementation in the same region (Indus Basin) [26].

Therefore, a methodological framework (Figure 3) was established to estimate the ET_a covering the study period (2003 - 2013) by the SEBS model for administratively important spatial units (basin, sub-basin, and provincial) and strategically viable time steps (annual, monthly and seasonal).

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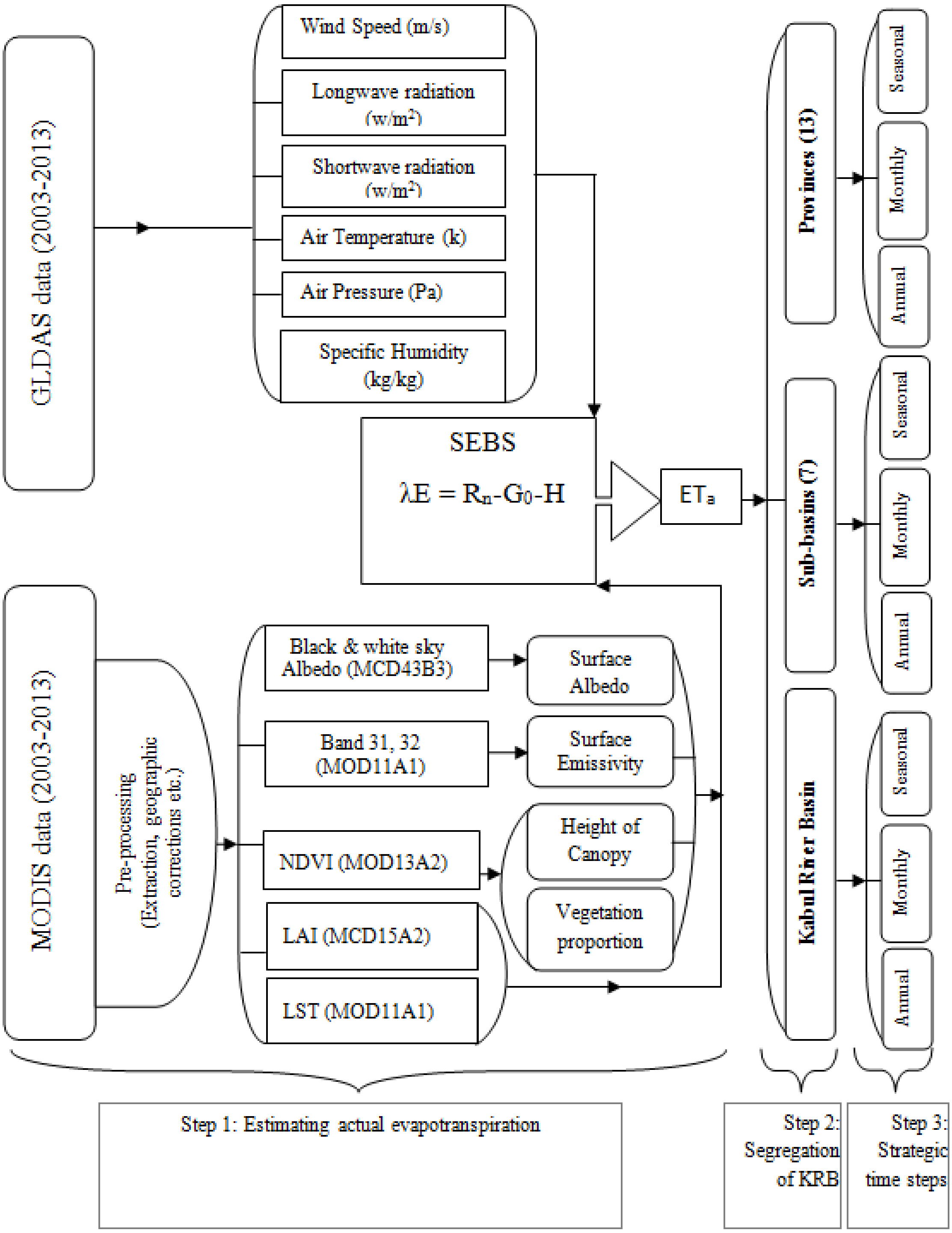

Figure 3: Methodological framework to estimate actual evapotranspiration in different spatial units of Kabul River Basin with strategic time steps

The SEBS algorithm is a single-source model used for the estimation of atmospheric turbulent fluxes and surface evaporative fraction derived from the remote sensing data. The SEBS algorithm employs meteorological and satellite spectral reflectance and radiance data for the estimation of the turbulent heat fluxes. It is based entirely on the rational of the basic equation used for the computation of surface energy balance, given below:

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$$R_n = G_0 + H + \lambda E \qquad \text{Equation 3}$$

where R_n is net radiation (Wm^{-2}) while G_0 is soil heat flux (Wm^{-2}), H is the sensible heat flux (Wm^{-2}), λE is the turbulent latent heat flux (Wm^{-2}) with λ being the latent heat of vaporization (Jkg^{-1}) and E is evapotranspiration.

Main input data Characteristics for the SEBS

The Global Land Data Assimilation System (GLDAS) is a unique uncoupled land surface modeling system that drives multiple models and integrates a large quantity of observed data purposed to ingest satellite and ground based measured data. It runs globally with a spatial resolution of 0.25^0 with 3 hours' step information [31]. The use of GLDAS datasets is very helpful while dealing with areas suffering from data scarcity or absence of the ground meteorological information [32, 33]. The meteorological variables (Table 1) extracted from the Goddard Earth Sciences Data and Information Services Center (GES DISC- http://disc.sci.gsfc.nasa.gov/hydrology) for tiles $H_{23}V_5$ which covers the study area which were used in the SEBS for the ET_a estimation in the data-scarce KRB.

Table 1: Characteristics of the climate parameters downloaded from Global Land Data Assimilation System (GLDAS) for a period (2003-2013) across the Kabul River Basin

S. No.	Data Type	Source	Variables	Spatial Resolution	Temporal Resolution	Temporal Coverage
1	GLDAS	NOAH	Wind Speed (m/s)	25km	3- Hours	2003-2013
2			Long-wave Radiation (W/m2)	25km	3- Hours	2003-2013
3			Air Temperature (K)	25km	3- Hours	2003-2013
4			Short-wave Radiation (W/m2)	25km	3- Hours	2003-2013
5			Air Pressure (Pa)	25km	3- Hours	2003-2013
6			Specific Humidity (Kg/Kg)	25km	3- Hours	2003-2013

The MODIS data sets (Table 2) used in the SEBS were downloaded from the Land processes Distributed Active Archive Center (LP DAAC) of the United States Geological Survey (USGS) (https://lpdaac.usgs.gov/products/modis_products_table). The downloaded meteorological variables were interpolated in a linear way to match the MODIS's temporal resolutions over-pass time over the KRB. While using the MODIS re-projection tool, the downloaded data sets were re-sampled by using the nearest neighbor interpolation method. The MODIS land surface temperature data is daily (instantaneous) product, while the leaf area index (LAI) is 8-day composite dataset. Because land surface status defined by LAI and surface reflectance or surface albedo (MCD43B3) does not alter significantly over short periods, therefore 8-days interval is enough to portray the land surface properties [34]. The land cover map (MCD12Q1) was used in the analysis of the evaporative behavior of different land cover types in the KRB.

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Table 2: Characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) products used in the estimation of ETa for a period (2003-2013) across the Kabul River Basin

S. No.	Data Type	Source	Variables	Spatial Resolution	Temporal Granularity	Temporal Coverage
1	Satellite Land Surface Data	MODIS	Emissivity/LST (MOD11A1)	1km	Instantaneous	2003-2013
2			NDVI (MOD13A2)	1km	16-day	2003-2013
3			LAI (MCD15A2)	1km	8-day	2003-2013
4			Albedo (MCD43B3)	1km	8-day	2003-2013
5			Land Cover (MCD12Q1)	500 m	Yearly	2003-2013

2.4. Evaluation of the SEBS actual evapotranspiration through Advection-Aridity model (AA):

The advection-aridity model (AA model) is an energy balance model [35] used in this study to estimate the actual evapotranspiration from the meteorological data of two stations, located at Nangarhar and Kunar provinces. The results of the AA model were used to evaluate the ET_a estimates of SEBS model. The AA model was chosen because of its suitability under arid and semi-arid conditions [26, 36, 37]. The main benefit of the AA complementary method is that it does not require any information on plant canopy resistance, stomatal resistance properties of the vegetation, soil moisture or other measures of aridity, because it depends mainly on meteorological parameters [35, 38]. The details of AA model have been elaborated in several studies under various geographic and climatic conditions [27, 39, 40]. The AA model [35] for regional evapotranspiration estimation which is based on Bouchet's complementary relationship [41], and expresses the ET_a as a combination of the wet environment (ET_w) and potential evapotranspiration (ET_p) (Equation 5):

$$ET_a = 2ET_w - ET_p \qquad \text{Equation 5}$$

where ET_a is the actual evapotranspiration, ET_w is the evapotranspiration under wet surface, ET_p is the potential evapotranspiration

2.5. Mann-Kendall test for monotonic trend in temperature

Trend in meteorological time-series is complicated because of its skewness, persistence and seasonality characteristics in data. Different researchers [42, 43] have used the non-parametric Mann–Kendall [44, 45] and Sen's [46]slope estimator. Several researchers [47] prefer the use of Mann-Kendall test because it provides the best alternative when the observed data is skewed either positively or negatively or otherwise correlated cyclic or serially [48]. Therefore to evaluate if there has been a significant monotonic upward or downward trend of the variable (temperature) over time that could trigger possible changes in the ET_a trend during 2003-2013, the Mann Kendall (MK) test was used which is applied to monthly inputs of the targeted variable. The monthly mean temperature (2003-2013) was used for the MK trend analysis test; the MK test statistics are calculated on monthly basis by

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using equation (7), while the variance (MK test) is computed by using equation (8). Beside this, MK statistic and its variance are used to calculate the cumulative MK statistics and variance by using Equations (9) and (10), respectively for a specific season/ year. Finally the cumulative MK statistic and variance is used to compute the Z statistic by the set of Equation (11).

$$S_i = \sum_{k=1}^{N-1} \sum_{l=k+1}^{N} sgn(x_{il} - x_{ik}) \ \forall_i = 1 \dots .12 \qquad \text{Equation 7}$$

where in equation (A), k, l = indices representing year k = 1,2…N, l = 2,3…N; i = indices representing month i = 1,2 …12; N = number of years; S_i = MK statistic for month i; x_{il} = data point for month i, year l; x_{ik} = data point for month i, year k and the function $sgn(x_{il} - x_{ik})$ is defined by:

$$\left.\begin{aligned} sgn\,(x_{ik}, x_{il}) &= +1 \ if \ x_{il} > x_{ik} \\ sgn\,(x_{ik}, x_{il}) &= \ 0 \ if \ x_{il} = x_{ik} \\ sgn\,(x_{ik}, x_{il}) &= -1 \ if \ x_{il} < x_{ik} \end{aligned}\right\} \forall l > k$$

$$sgn\,(x_{ik}, x_{il}) = undefined \quad for\ l \leq k$$

When each time step is shown by a single data point (with sample size > 10), then the variance of MK statistics is calculated through the following equation:

$$VAR(S_i) = \frac{1}{18}\left[N_i(N_i - 1)(2N_i + 5) - \sum_{p=1}^{g_i} \left(t_{ip}\left(t_{ip} - 1\right)\right) 2t_{ip} + 5)\right] \qquad \text{Equation 8}$$

where g_i = number of groups with tied data in month i; t_{ip}= number of tied data points in group p of month i; and N_i = number of data points (over years) for month i.
After calculating S_i and VAR(S_i) for individual month, the annual sum was calculated by using equations C and D:

$$S^* = \sum_{i=1}^{k} S_i \qquad \text{Equation 9}$$

$$VAR(S^*) = \sum_{i=1}^{k} VAR(S_i) \qquad \text{Equation 10}$$

The standardized Z_{MK} statistics were calculated using the following equation which follows a standard normal distribution and can be related to a P value for testing the significance of the trend [49]:

$$Z_{MK} = \frac{S - 1}{\sqrt{VAR(S)}} \ if \ S > 0 \qquad \text{Equation 11}$$

$$Z_{MK} = 0 \ if \ S = 0$$

$$Z_{MK} = \frac{S + 1}{\sqrt{VAR(S)}} \ if \ S < 0$$

3. Results and Discussion

3.1. Validation of the ET_a estimated through SEBS with AA Model estimates

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Based on the validation results shown in figure (4), there has been a sound fitness between the ET_a estimated through SEBS and ET_a estimated through AA at Kunar and Nangarhar provinces. The coefficients of determination thus obtained were R^2=0.81 and R^2=0.77, respectively. For the cool months of the year, the ET_a values of AA model are lower than those of SEBS. The reason behind is that the AA model uses a form of the Penman equation which does not work fine for those periods for which the available energy (R_n) is negative or otherwise very close to zero. A similar result has been obtained from another study [50] whereby they estimated ET_a through Complementary Relationship Areal Evapotranspiration (CRAE) and AA models which resulted into lower values by using AA model against those of CRAE in the cool months of winter. Another study in the Indus Basin [26] also shows that the ET_a calculated through AA was lower in the cool months of winter (October to March) compared to ET_a estimates through SEBS for the same period. The AA model yields lower value of ET_a under high precipitation conditions [36] which goes in line with the result of this study.

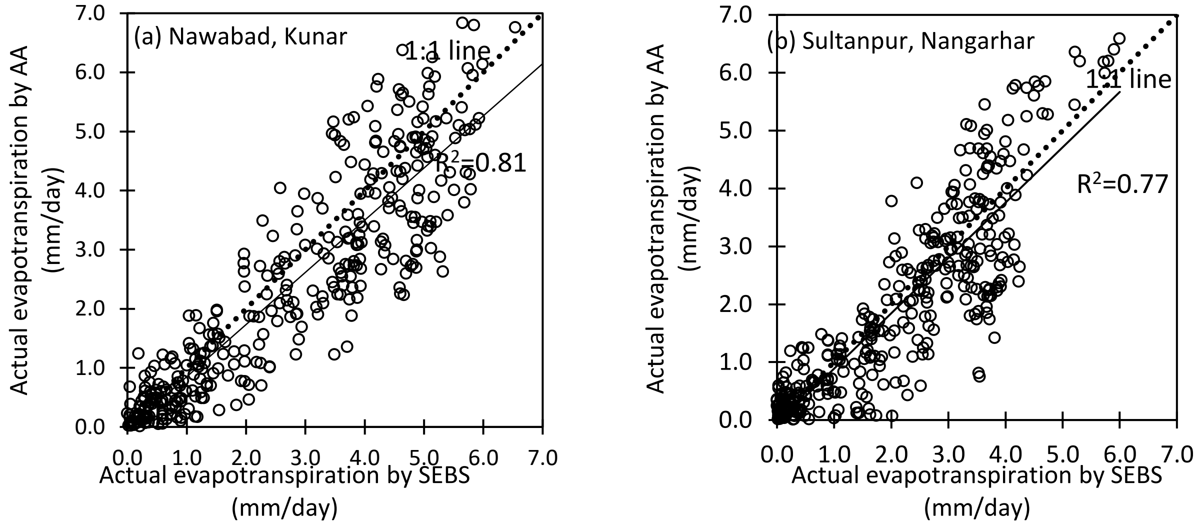

Figure 4: Comparison of the actual evapotranspiration estimated through SEBS algorithm and AA model at (a) Nawabad (Kunar) and (b) Sultanpur (Nangarhar) stations of the Kabul River Basin

3.2. Annual distribution of actual evapotranspiration across the KRB, constituent sub-basins and provinces

There is around 9% increment in the mean annual ET_a of KRB from 2003 till 2013, with around 2% of agricultural land cover expansion across the KRB [12]. The LULC analysis as well as the secondary data [51] shows that from 2003 till 2013 there have been increase in the cultivation of wheat and rice across the country which are the main staple foods in Afghanistan. The minimum mean annual ET_a was estimated for the Chak aw Logar sub-basin (i.e. 420±21 mm); the relatively higher standard deviation has been caused by the drought conditions in 2004 which caused a drop of 19% in the ET_a in Shamal sub-basin with respect to 2003. In comparison to 2003, Kunar sub-basin experienced the highest increase (13%) in the mean annual ET_a while Alingar experienced the least increase (4%). The outliers in the box-plot (Figure 5) for Shamal, Kunar and Gomal subbasins show the effects of drought in 2004 which were dominant in the mentioned sub-basins. In reference to 2003, Nangarhar province experienced the highest increase in the ET_a (15%) in 2013 followed by Khost

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province (12%) while Paktya province experienced around 8% reduction. The reason for increase in Nangarhar and Khost province might be agricultural infrastructural development leading to irrigated land area enhancement as well as resultant increased crop rotation compared to a decade earlier. While reduction of ET_a in Paktya province is perhaps due to the reduced water supply for irrigation purpose.

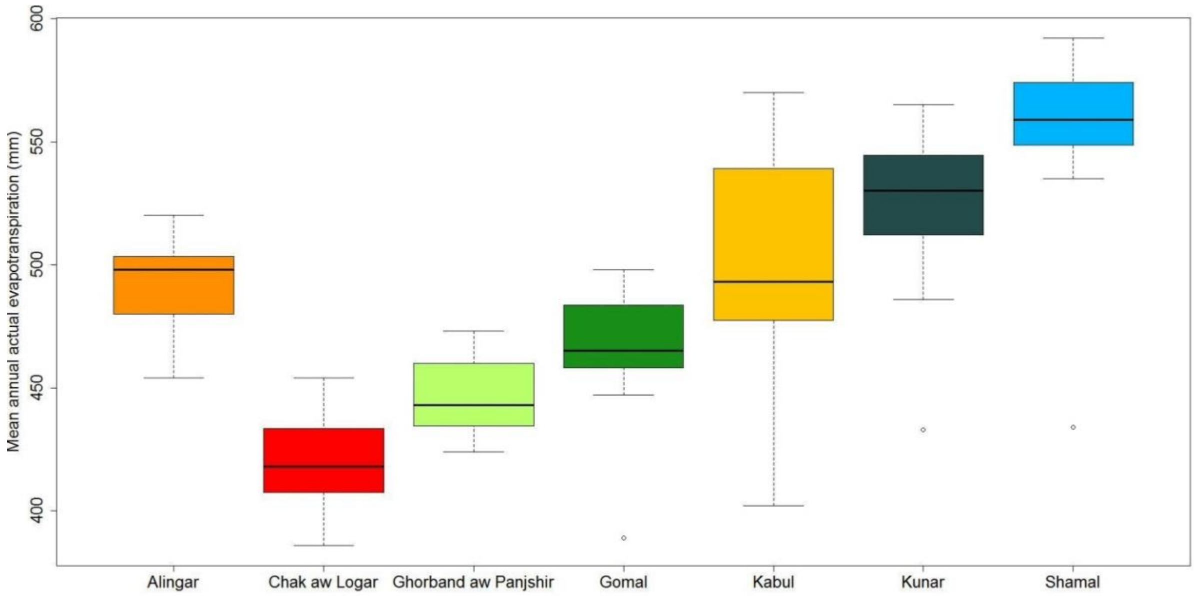

Figure 5: Box and whiskers plot of annual evapotranspiration (ET_a), showing the temporal (2003-2013) and spatial variation of the ET_a. The horizontal line inside each box represents the median, the lower and upper whiskers show the ET_a range during the study period.

3.3. Monthly distribution of actual evapotranspiration across the KRB, constituent sub-basins and provinces

The mean annual ET_a shows that the usual highest values of ET_a across the KRB are in the months of May-July which are around 70±1.6 mm. The seasonal variability in the ET_a in summer season (May-Sep) across the KRB stays almost consistent with a seasonal mean ET_a of 333±19 mm. Overall, the least monthly mean ET_a for the month of January and December across all the sub-basins was 9±3 mm) and (7±1 mm) respectively. (Figure 6a).

The Panjshir province experienced the lowest mean ET_a in winter season during the study period. Contrary to these estimations, another study [52] estimated 570 mm as the seasonal ET_a (May-Sep) being an average of 3 years (2003-2005) for which estimates of the current study for the very period is about 259 mm. High level of ET_a estimations in the Kabul province by another study [52] may be due to tendency of SSEB's overestimation of ET_a both at local and regional scales probably due to rainfall contributions and abundant soil moisture that naturally supplement crop water needs [53].

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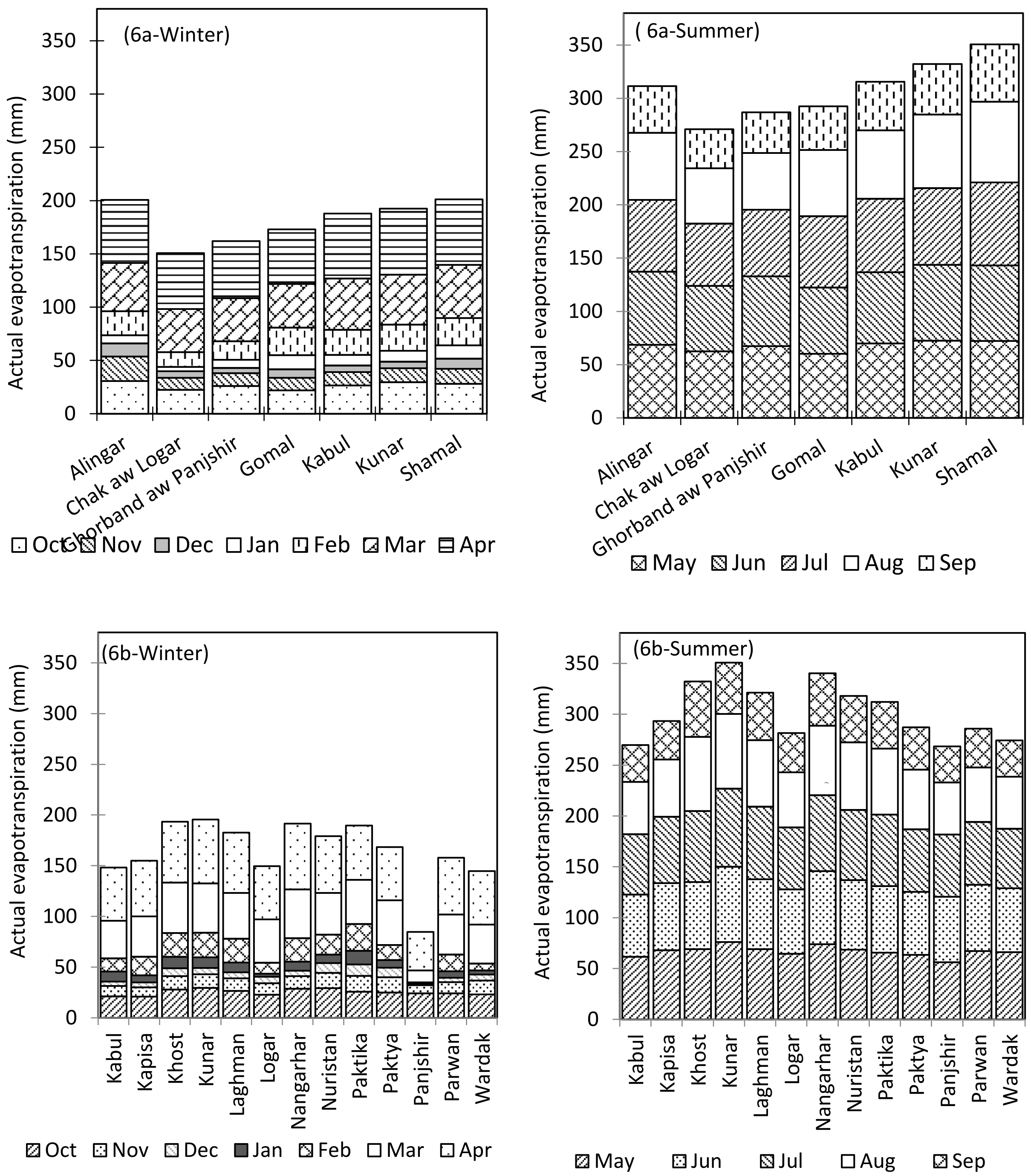

Figure 6: Mean seasonal (2003-2013) variation of actual evapotranspiration in winter and summer seasons at the (6a) sub-basins and (6b) provinces of the Kabul River Basin (Note: The statistical details have been explained in the text)

A routine inter-seasonal comparison of ET_a in summer and winter shows a higher range of ET_a in summer 2013 compared to that in winter 2012-2013 (Figure 7). The reason standing behind is the peak irrigation demand, favorable meteorological conditions for crop growth, diversity and abundance of crops, vegetables and fruit orchards mostly in the summer season while winter is limited to fewer crops and is mostly dominated by wheat and barley etc.

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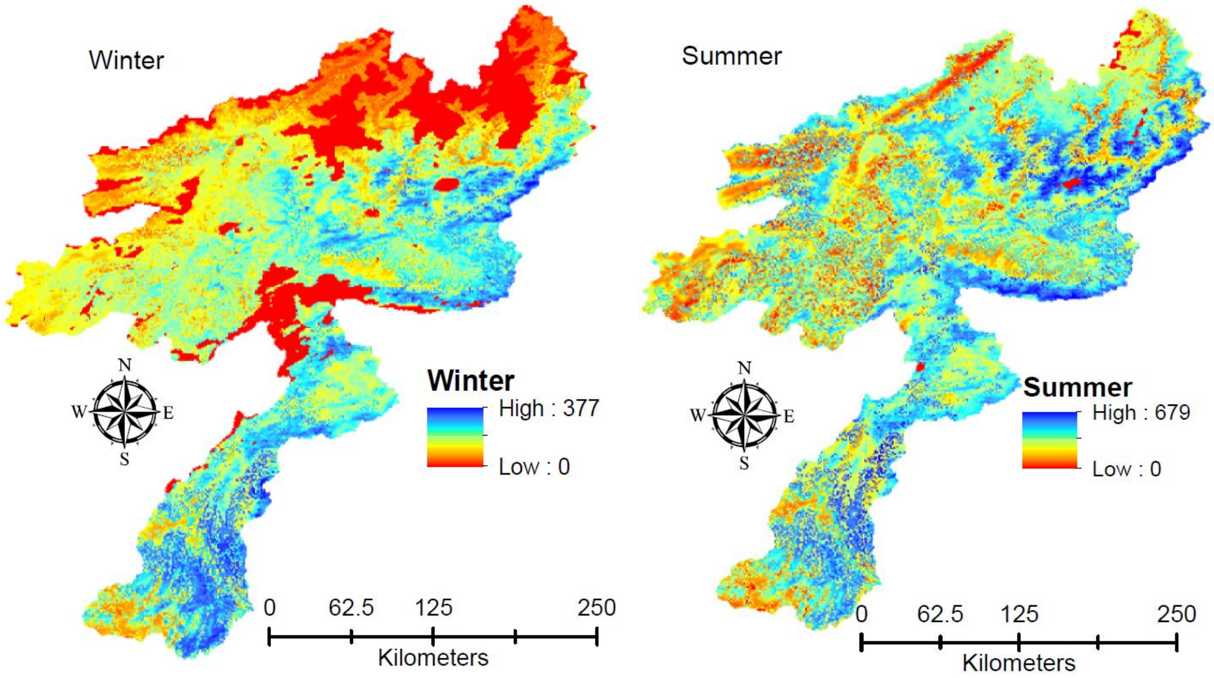

Figure 7: Seasonal distribution of actual evapotranspiration (mm) during winter (October-April, 2012/2013) and summer (May-September 2013) in the Kabul River Basin

3.4. Land cover based variation of ET_a across the KRB

The land cover based ET_a results show a high ET_a in the areas with maximum precipitation that usually falls in the months of November-March which has been used in the peak irrigation period with various frequencies.

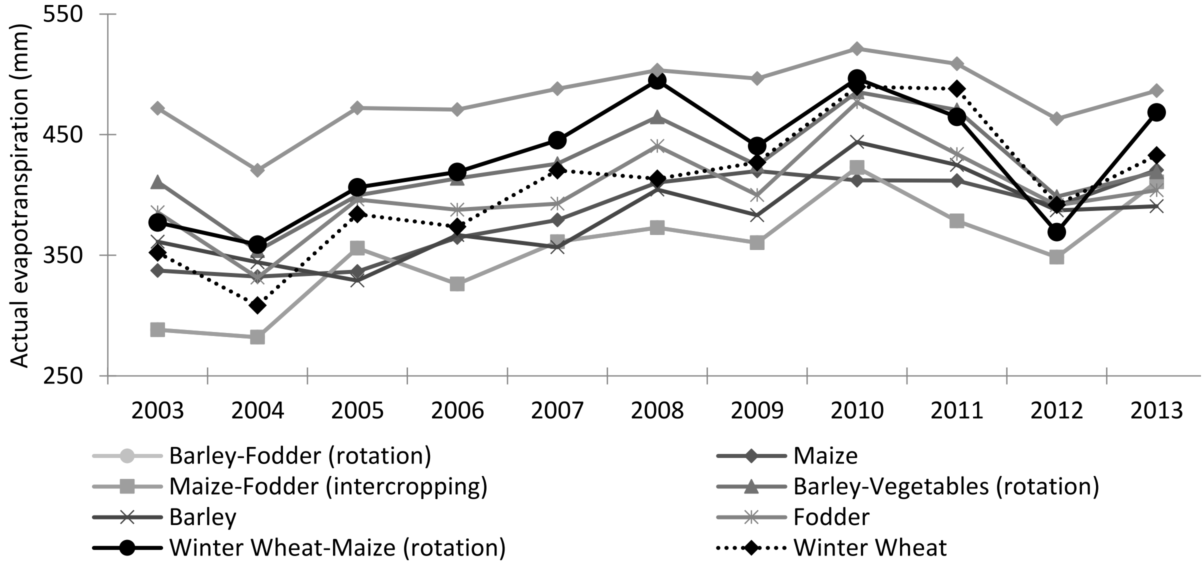

Figure 8: Land cover based distribution of actual evapotranspiration of main cereals across the Kabul River Basin 2003-2013

Among crops, wheat is the highly consumed and cultivated crop across the KRB. It is normally cultivated in rotation with maize and rice mostly in downstream of the KRB

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dominantly on irrigated lands while in the central KRB, It is cultivated with fruit orchards in contrast to the downstream regions. Therefore, from 2003-2013 the mean annual ET_a of wheat-maize, wheat-rice and wheat alone across the KRB was 377±49, 472±27 and 352±54 mm, respectively. For wheat, results from the neighboring Uzbekistan show ET_a values for wheat to be 397 mm [54].

3.5. Evaluation of the irrigation performance

3.5.1. Evaluation of the results of Mann-Kendall test for monotonic trend in temperature

Mann-Kendall test has been used for the statistical analyses of the trend detection in temperature data from 2003 to 2013 (11 years). It was observed that there is no significance trend found in the temperature time series data of the KRB that could possibly influence the monthly ET_a values in a trending way. The resultant mean P-value for the entire study period was 0.53, greater than the significance level (α=0.05) which lead us to accept the null hypothesis (H_0) (Table 3).

Table 3: Mann-Kendall test statistics for monotonic trend in temperature

	Observations	Std. deviation	Kendall's tau	S	Var (S)	p-value (Two-tailed)	Alpha (α)	Z_{MK}
Jan	11	1.0	0.2	9.0	165.0	0.53	0.05	0.70
Feb	11	0.7	0.1	5.0	165.0	0.76	0.05	0.39
Mar	11	2.5	0.1	5.0	165.0	0.76	0.05	0.39
Apr	11	1.9	0.1	3.0	165.0	0.88	0.05	0.23
May	11	1.9	0.2	13.0	165.0	0.35	0.05	1.01
Jun	11	1.5	-0.1	-5.0	165.0	0.76	0.05	0.39
Jul	11	0.7	0.2	13.0	165.0	0.35	0.05	1.01
Aug	11	0.7	0.5	25.0	165.0	0.06	0.05	1.95
Sep	11	0.7	0.1	7.0	165.0	0.64	0.05	0.54
Oct	11	1.4	0.2	13.0	165.0	0.35	0.05	1.01
Nov	11	1.2	0.2	11.0	165.0	0.44	0.05	0.86
Dec	11	0.9	0.2	11.0	165.0	0.44	0.05	0.86
Mean		1.3	0.2	9.17	165.0	0.53	0.05	0.78

3.5.2. Analysis of spatial Equity

A recent study in the KRB [12] shows that ratio of cropped to non-cropped area varies substantially among different provinces and sub-basins. Thus, comparing the ET_a for total area by considering cropped and non-cropped between the provinces and sub-basins will be misleading. We, therefore, delineated the cropped area from the non-cropped area and hence used the ET_a from the cropped area among different provinces. (Figure 9). Moreover, different cropping patterns in different sub units would result in different RET values and hence the comparison of adequacy will be misleading. However, the irrigation system of KRB is supply based rather than demand based. The supply based irrigation system provides thin layer of equal amount of water to different sub units regardless of the cropping pattern [8]. Therefore, the limited and equitable water amounts to all sub units restrict the farmers to grow similar crops. Results of [12] also shows that cropping patterns in KRB does not vary substantially in different sub-basins and provinces.

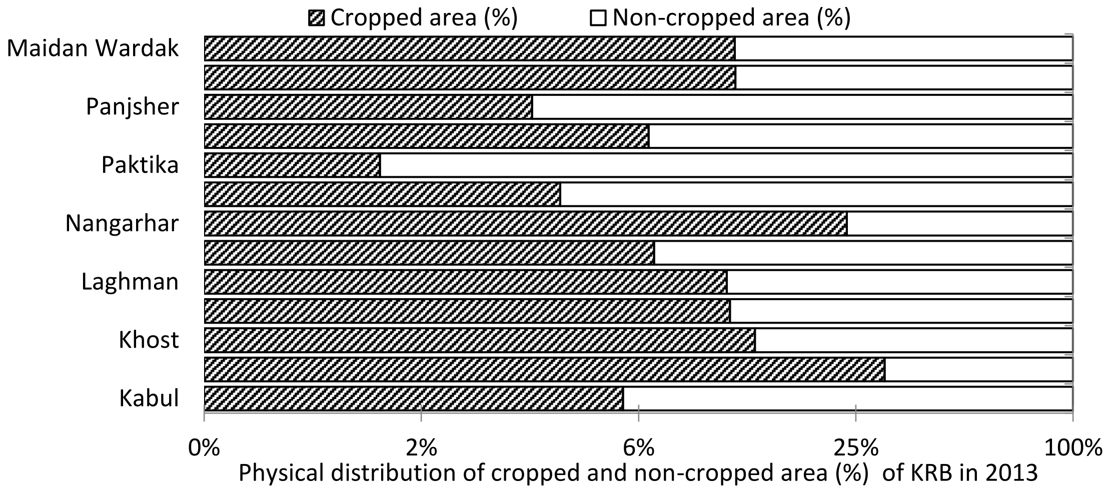

Figure 9: Physical distribution of cropped and non-cropped area of the KRB

The results in Figure 10 shows that, generally, in winter season the CV of mean ET_a in the months of Oct-Jan are the least (0.09±0.04) for all the sub-basins which show that greater equity exists among the sub-basins during the colder months of the year where there is no irrigation required. The highest CV was assessed for Chak aw Logar (0.41) in the month of February followed by the second highest CV in Shamal (0.35) and Kabul (0.33) sub-basins during the peak irrigation period (e.g. in the month of April) (Figure 9a). The reason behind the highest CV in the month of February is the earlier season warm up and raised temperatures which melt down the snow and contribute to the irrigation period. The high CV values for Kabul and Shamal sub-basins is perhaps due to the steady melting of the snow packs on the tops and contribution to the peak irrigation season which is usually February to May.

Moreover, this sub-basin hosts the most irrigated area compared to the remaining sub-basins of the KRB. In summer season, there high inequity in Kabul sub-basin compared to the others. Similarly the spatial variation of CV in Panjshir province among the provincial units shows highest CV for the months of Oct, Nov and April in the months with higher temperatures but equity was assessed during cooler months. Generally the CV for areas with larger irrigation areas was higher than those with more rainfed agriculture which shows high inequity among spatial units of the KRB.

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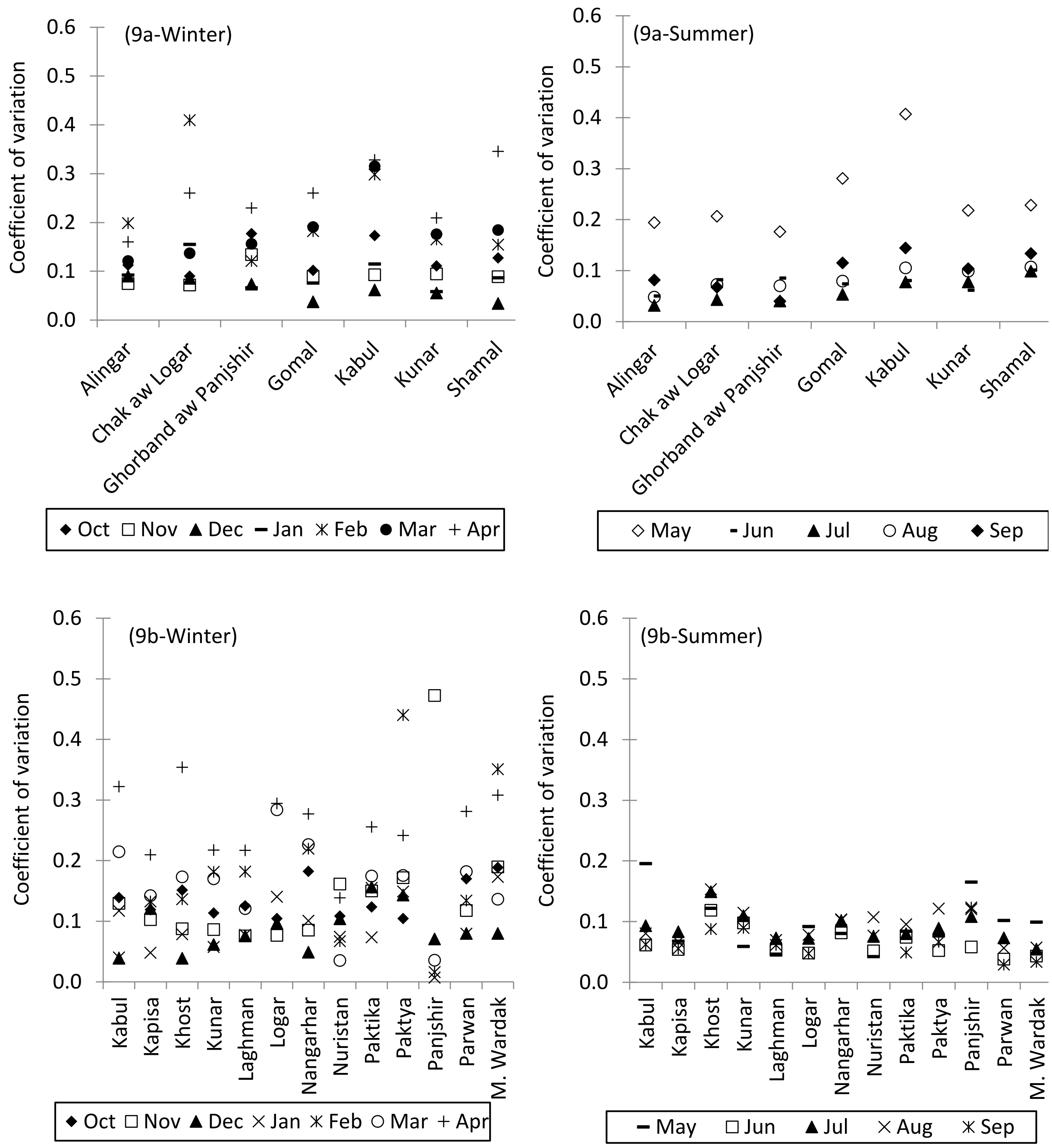

Figure 10: Coefficient of variation of mean actual evapotranspiration at the spatial administrative units of (9a) inter and intra sub-basin and (9b) provincial level

3.5.3. Analysis of Seasonal Adequacy

Throughout the KRB, the mean maximum RET for summer (May-September) and winter (October-April) was 0.84 and 0.73, respectively (Figure 11). In the irrigated parts of the KRB, the RET, estimated both for summer and winter, was below the critical value (i.e. RET≤ 0.65). Similarly areas where ET_a and ET_c are closer to each other (RET>0.65), they are elevated at higher altitudes with either snow cover or otherwise forested.

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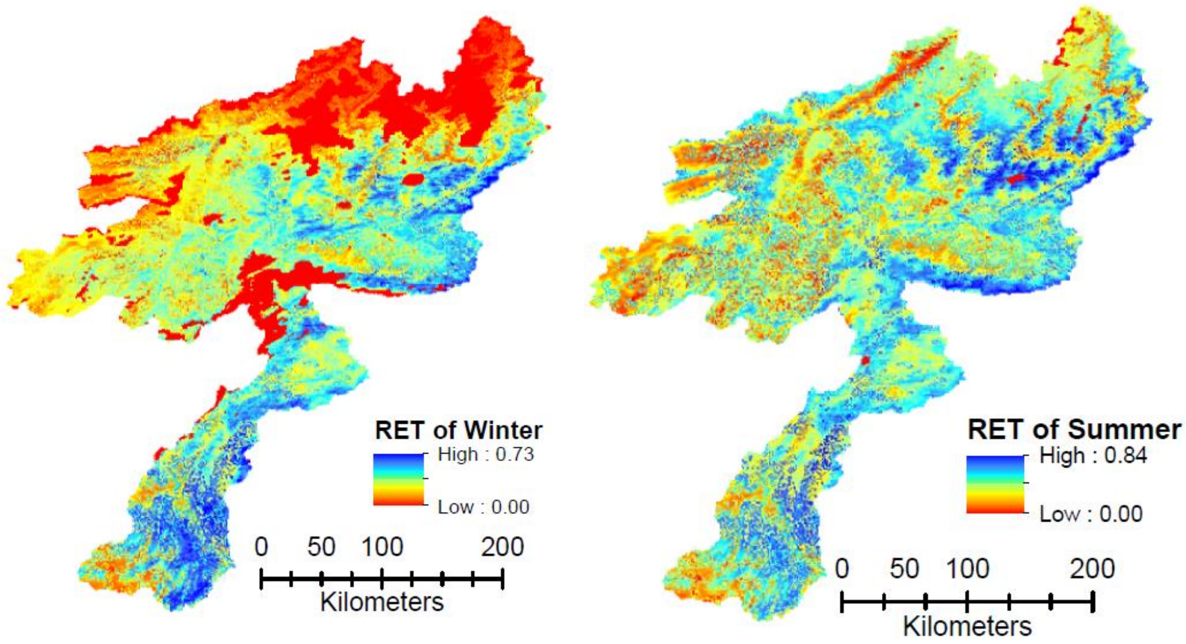
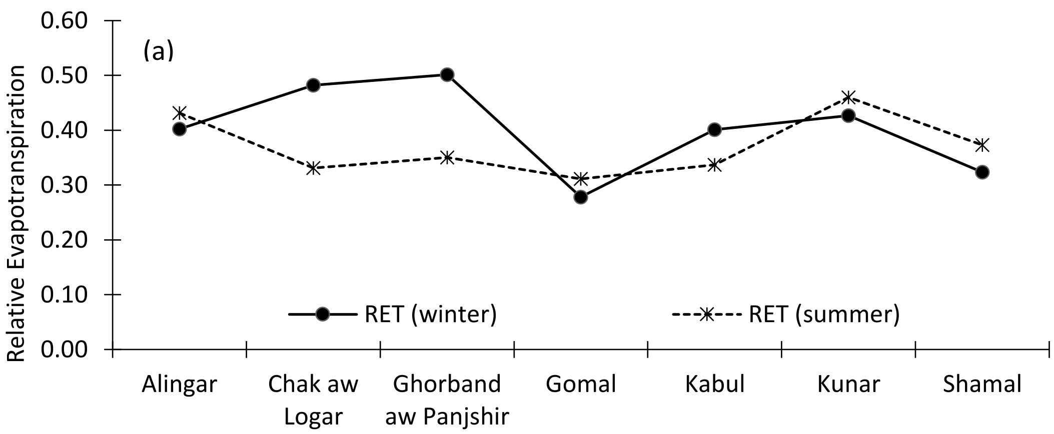


Figure 11: Seasonal (Winter and Summer) relative evapotranspiration distribution across the Kabul River Basin

For winter season, the highest RET for Ghorband aw Panjshir and Chak aw Logar sub-basins was 0.50 and 0.48 respectively while the lowest RET was at Gomal sub-basin (i.e. 0.28) (Figure 12). The reason for higher RET in Ghorband and Panjshir and Chak aw Logar sub-basins might be the lower temperatures, and also low irrigation demand as a consequence of early stages of crop development with low water demand.

Overall, the RET for winter season is higher than that of in summer. For summer season the highest RET was experienced by Kunar and Alingar sub-basins which was 0.46 and 0.43 respectively. While for remaining sub-basins the RET was in the range of almost 50% of the critical value of RET, i.e. Chak aw Logar (0.33), Ghorband aw Panjshir (0.35) Gomal (0.31), Kabul (0.34) and Shamal (0.37). The comparative higher RET in Kunar and Alingar could be attributed to the presence of less irrigated areas compared to the rest because Kabul sub-basin hosts the highest irrigated land area compared to the rest and therefore stays under stress during the peak irrigation season which takes place from month of April onwards.



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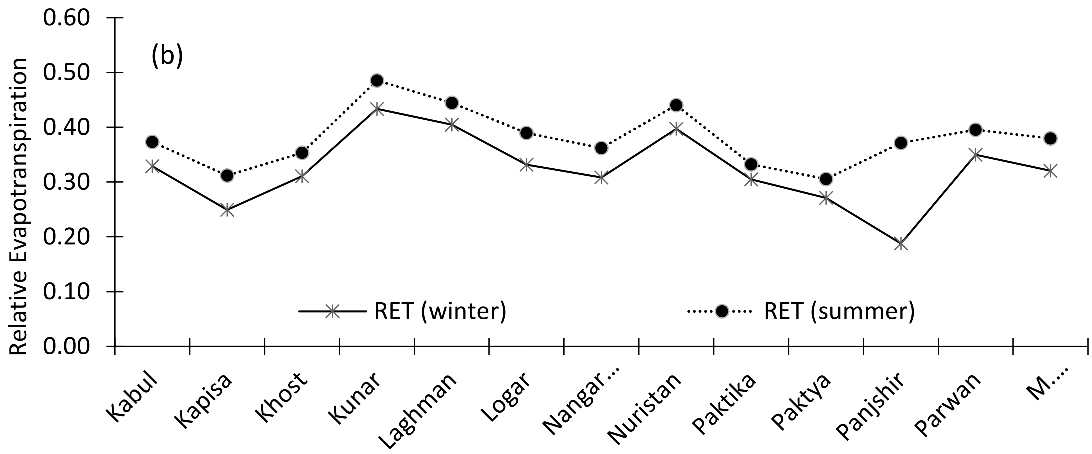
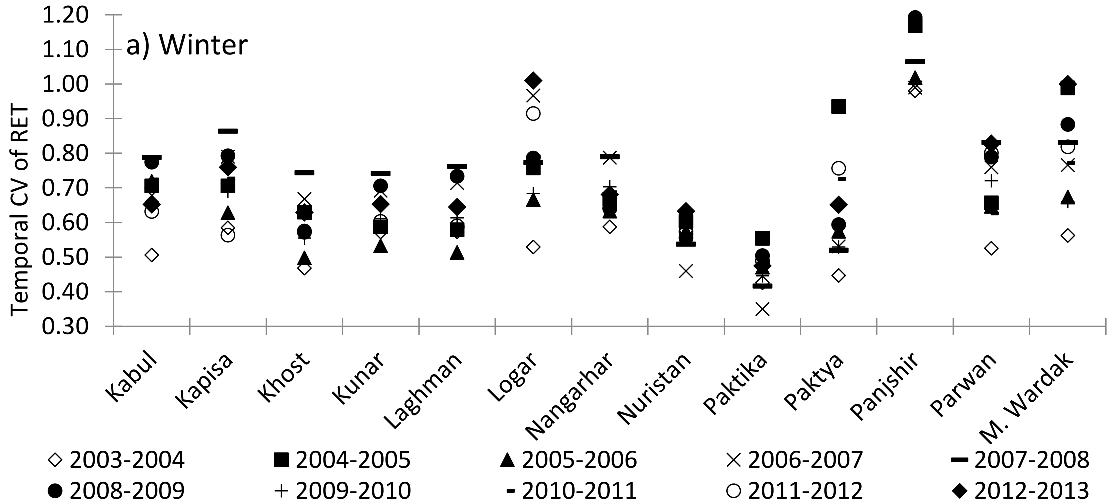


Figure 12: Inter and intra distribution of relative evapotranspiration across (a) sub-basins and (b) provinces of the Kabul River Basin in winter and summer seasons

3.5.4. Analysis of temporal Reliability

The temporal reliability of water supplies for irrigation purpose in the KRB was evaluated by using the CV of RET at all the constituent provinces of the KRB shows that the CV of RET in winter (Oct-Apr) is usually higher than that of winter season. The higher CV in winter is strongly driven by the higher CV of RET especially in the months of Feb-Apr (winter) and May (summer) (Figure 13) because it is the time where irrigation starts based on the irrigation water demand and temperatures are on rise, and therefore unreliability of water supplies are experienced for the crops grown across the basin.

The temporal expression (2003-2013) of the CV of RET in winter season showed a large variation in provinces of Panjshir (CV ≥0.98), Paktya (CV = 0.45-0.94) and Logar (CV = 0.53-1) provinces. Perhaps one of the reasons for the large variation in the CV of RET in these provinces is because of their relatively small irrigated land holding. Beside this the effect of wet (2003, 2005, 2007, 2009, 2013) and dry (2000, 2001, 2002, 2004, 2006 and 2008) years (Pervez et al., 2014) might be also driving the temporal variation in the RET across the provinces of the KRB.



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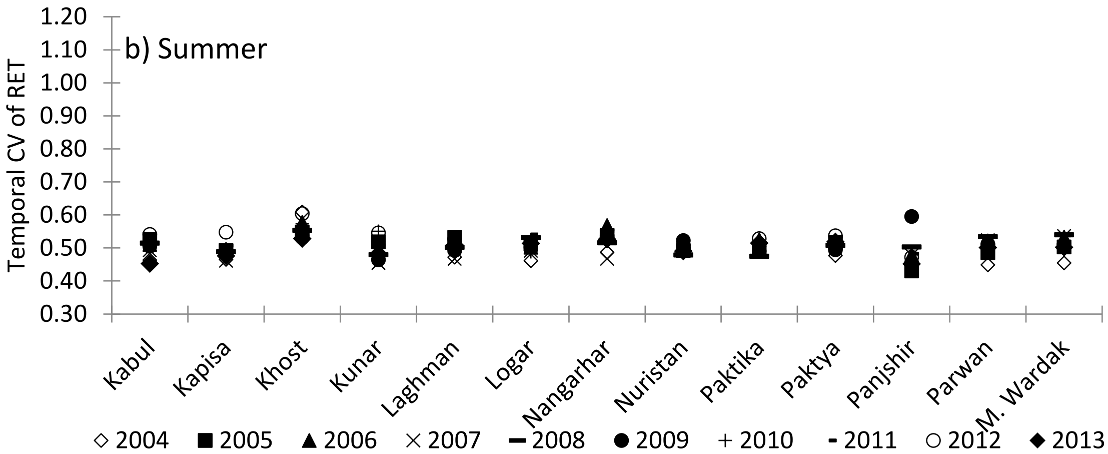

Figure 13: Temporal coefficient of variation (2003-2013) of relative evapotranspiration during a) winter and b) summer

Similarly, in summer season (May – Sep), throughout the study period, the fluctuation in the CV of RET has largely been affected by the higher CV in the month of May. It is perhaps due to the fact that maize and some local vegetables are being grown in this month where fields are irrigated to bring them to a field capacity level for creating a germination friendly crop-soil-moisture atmosphere.

Throughout the study period, across all the constituent provinces of the KRB, the CV of RET varied within a range of 43%-60% which is quite narrow compared to that of winter season. Likewise in winter season, the range of CV of RET in summer was high in Panjshir province whereas the highest CV of RET was 0.60 in the year 2009 which is considered to be a wet year by receiving more precipitation than a normal year. Panjshir province is located at the upstream heights of the KRB which receives a larger share of the annual precipitation which is a result of melt is flown downstream and contributes to the irrigation network in the KRB. After Panjshir province, Nangarhar province has the highest range of the CV of RET during 2003-2013 which receives the snow-melt from the upstream in the form of river discharge and therefore is the largest irrigated land holding province in the KRB by enjoying crop rotation (i.e. usually two crops per year). It shows that largest irrigated part of the KRB is largely suffering from the unreliable water supplies both in summer and winter. Nuristan province has the narrowest range of the CV of RET (0.49-0.52), it can be reasoned as the mountainous land area with dominant forests and limited cropped area which receives rainfall (other than winter precipitation in the form of snow) that contribute to its canals for irrigation purpose each year due to the fringe effect of monsoon from Himalayas.

During the study period, the larger CV range of the RET shows that the supply based irrigation system in the KRB delivers unreliable water supplies to the users which requires management interventions for raising water productivity across the KRB hosting the highest population of the country compared to any other basin in Afghanistan. The different ranges of the CV of RET at different provinces is driven by various factors, e.g. geographic location (upstream-receiving the snowfall as the winter precipitation or downstream as the recipient of the snow-melt, topographic relief and canal network existence, and certainly management interventions by the relevant department and ministry plays a role too.

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4. Conclusion and recommendations

Decades of political instability and conflicts caused infrastructural damage and ultimately led to data scarcity on land and water resources in Afghanistan. Agriculture sector consumes around 98% of the total water withdrawn for irrigation purposes. Having consumed such a high amount of water for agriculture, the country's dependency on foreign food imports highlights the inefficiency of the irrigation system as well as the responsible institutions. In order to sustainably manage these water resources, it is extremely important to analyze the long-term operational and strategical performance of the irrigation system. To assess the irrigation performance for around a decade (2003-2013), we identified those set of indicators which requires minimum secondary data which is very effective in data-scarce basins like the KRB. The irrigation performance assessment in the KRB shows that the irrigation system in the KRB is experiencing inequity, inadequacy and unreliability especially during the peak demand period which results into inefficient irrigated agriculture and poor crop-water productivity. It therefore leads to larger voids between water demand and supply and ultimately leads to failure to meet the growing food demand across the country. Beside water losses that occur during conveyance and application, it affect other water consuming sectors too which are deemed to have increased water needs in case of industrial and municipal developments in the near future. The relevant platforms need to strategically invest in the development of irrigation infrastructure (e.g. canal lining, water storage structures etc.) as well as capacity development of the local manpower at the Ministries of Agriculture, Irrigation and Livestock as well as Ministry of Energy and Water to safeguard the irrigation quota for the dominant crops especially in the peak demand period. As shown in the study the relative evapotranspiration across all the sub-basins shows the entire KRB, hosting around one-third of the country's population, to be under water stress which needs to be addressed and managed in order to meet the growing water and food demand in the country. The ET_a derived under this research could also be used in comparisons to future studies over the effects/impacts of climate change on ET_a. Furthermore, the results of this study will considerably contribute to the investment plans addressing water resources management issues in the Kabul River Basin.

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