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Assessing Water Consumption Pattern and Delivery Irrigation Performance Indicators Using the WaPOR Portal Under Data-Limited Conditions, Ethiopia

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Abstract

Enhancing water use efficiency hinges on improving water consumption and the performance of irrigation systems. Nevertheless, challenges such as limited access to historical and current data, difficulty in securing continuous data, conflicts, the inability to cover vast areas, and high costs impede the monitoring and assessment of irrigation performance. This study aims to evaluate the water consumption patterns and irrigation performance indicators using open-access datasets. The study demonstrated the actual evapotranspiration and irrigation performance indicators, including water productivity, equity, adequacy, relative water deficit, and beneficial fraction. QGIS and ArcGIS were used to conduct spatiotemporal analysis on the locations of irrigated fields (lower, middle, and upper) across the Koga irrigation scheme. The WaPOR datasets on water, climate, and land, with a spatial resolution of 30 m and real-time temporal resolution, were used for the analysis of the irrigation scheme. The findings indicated that in the 2018 irrigation season, the minimum values for actual evapotranspiration, transpiration, biomass, and yield were 439 mm, 326 mm, 5.9 t ha^{-1}, and 2.8 t ha^{-1}, respectively. The estimated delivery performance indicators were categorized as poor for adequacy and relative water deficit, fair for equity, and acceptable for beneficial fraction. These outcomes provide insights into the features of irrigators and the overall trends in irrigation systems. The spatial and temporal analysis of delivery performance indicators highlighted that agronomic practices, management, and operations are the factors contributing to water scarcity in the irrigation scheme. In conclusion, our findings highlight that open-source data offers valuable insights for evaluating and overseeing water consumption and the performance of irrigation schemes in data-scarce regions.

Keywords: Biomass; Evapotranspiration; Irrigation performance; Koga irrigation scheme; WaPOR.
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1. Introduction

Water plays a pivotal role in economic activity and human well-being, particularly in irrigation and domestic use,[1] as indicated in Sustainable Development Goals 6. When compared to other water users in a basin, irrigated agriculture is the largest consumer of freshwater. A “water short” basin tends to have more conflicts if water is not properly allocated among different users.[2] Natural basins have gravity-driven water flow, and residents upstream might theoretically alter the water's course. This can be the basis for water conflict.[3] Conflicts over water are often caused by competition for water resources, particularly during the dry season.[4] Therefore, assessing the irrigation performance indicator within an irrigation scheme presents an alternative approach for addressing issues related to water conflict and water allocation. The performance evaluation of the irrigation project is a crucial management tool to increase the irrigated agricultural system's environmental sustainability, best management practices adoption, and financial viability.[5] It is important to evaluate the performance of the irrigation projects

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continuously to identify bottlenecks, constraints, managerial gaps, and other grey areas in the system and to provide a direction for improvement in water resource development and management strategies to reap its full benefits on a long-term basis. Several studies have been conducted worldwide for the performance evaluation of irrigation projects.[6,7] For instance, the International Water Management Institute, Sri Lanka, in their Research Report No. 20 suggested the indicators for comparing the performance of irrigated agricultural systems, the researchers[8] compared the performance of eighteen irrigation systems located in eleven different countries through various indicators.

In Ethiopia, approximately 90% of the irrigation potential in terms of land and water resources remains undeveloped. However, there have been many ongoing medium and large-scale irrigation developments in recent years. While approximately 47% of the cultivated land is dedicated to extensive public irrigation projects, the primary focus of these initiatives is the cultivation of industrial crops such as cotton, sugarcane, and a variety of fruits, rather than the successful sustenance of cereal crops like wheat. Approximately 65% of the irrigated area is under small-scale irrigation schemes, either modern or traditional.[9,10] The availability of irrigation water management information on a detailed scale like farmer fields or entire river basins is uncommon and is not continuous. Data to quantify performance indicators are rarely collected and when collected, data is often unreliable or not easily accessible.[11,12] This is also true in Ethiopia, particularly in the Koga irrigation scheme.

To make a performance-oriented approach effective, it is necessary to retrofit new techniques and approaches to existing management practices.[13] Satellite measurements can provide regular information on the agricultural and hydrological conditions of the land surface. The authors[13-15] present earlier reviews on remote sensing applications for irrigation management. In many nations, but especially in Ethiopia, a dearth of sufficient, adequacy, and timely irrigation statistics makes it difficult to accurately assess the efficacy and sustainability of irrigation systems. Then, to overcome the challenges of irrigation performance assessment in the irrigation scheme, initiating a researchable concept related to open-access data sources is fundamentally crucial.

Increasing water productivity is of vital importance given the growing competition for water in Ethiopia. To better perform an intervention to improve crop water productivity, additional analysis must ascertain the underlying causes of good and bad crop water productivity levels.[16] Crop water production is governed only by transpiration because transpiration is a pivotal factor in crop water production as it accounts for a significant portion of the water that plants absorb from the soil and release into the atmosphere. As it is difficult to separate transpiration from evaporation from the soil surface between the plants (which does not contribute directly to crop production), defining crop water productivity using evapotranspiration rather than transpiration makes practical sense at the field and system level.[17,18] Due to this, most research papers did not consider water productivity separately for surface and canopy evaporation.[19] Land productivity and water productivity have fallen below the regional average, as indicated by both published and unpublished data.[20] The Koga irrigation scheme's performance was hindered by soil acidity, inefficient water use, water scarcity, and a lack of market connections,[21] However, it was evident that farmers possessed limited awareness of irrigation water management.

In today's context, the utilization of open-access data offers significant advantages when analyzing water resource management aspects across both space and time. Among the invaluable resources available, WaPOR stands out by providing comprehensive and up-to-date information on water management systems and facilitating a detailed performance analysis of irrigation performances at finer resolutions. This remote sensing tool plays a pivotal role in bridging the gap caused by limited observational data, inability to cover extensive geographical areas, and financial constraints. Furthermore, it is the sole open-access resource applicable in the study area for water and land productivity analysis. Thus, Food and Agricultural Organization of the United States (FAO) water productivity open access portal (WaPOR version 2) is used for this research to assess the water resource management and irrigation performance analysis scheme.

This research endeavors to assess the effectiveness of quality criteria governing irrigation water delivery services, while also examining the temporal and spatial variations in water consumption. Such a comprehensive evaluation offers valuable insights to irrigation managers and farmers, helping them surmount the challenges associated with water distribution, water scarcity, and potential conflicts within the irrigation scheme. This study thus plays a pivotal role in ensuring the sustainability and productivity of agricultural practices reliant on irrigation. The objectives of this research

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are: 1) to assess water consumption and water delivery irrigation performance indicators; 2) to provide insights and maximize the irrigation water supply and delivery for better agricultural water management using remotely sensed (WaPOR) ready-made open-source data within the observed data-limited areas.

2. Material and method

2.1 Location

The study was conducted at the Koga irrigation scheme in the Amhara National Regional State (ANRS), Ethiopia (Fig. 1). The Koga irrigation system has the principal components of the dam reservoir and irrigation drainage system. The irrigation scheme management, maintenance, and operation are conducted at the main and tertiary systems. The irrigation scheme was divided into 12 irrigation blocks. The cultivated potential area of the irrigation scheme is 7004 ha and has eleven-night storages for delivering water to the tertiary canal.

Six irrigation blocks were taken into consideration to sample the raster values from the satellite-based datasets, depending on the information provided by the Koga Irrigation Development Office implementation report (Table 1). The irrigation blocks were categorized as upper, middle, and lower blocks due to their position and the alignment of the irrigation scheme. A total of 797 sample farm plot geographical coordinate points (upper section 189, middle section 281, and lower part 327 points) were taken from farm plots located in each irrigation block (Fig. 1). This enabled the extraction of the pixel values from the raster files using a raster layer sampling algorithm and helped to generate information at farm plot levels. In this study, the wheat crop is selected as a test crop; this is because the majority of the households (89%) are irrigated wheat due to its market demand and 11% of households are irrigated wheat because of its ease of management and grain storage.[22] Currently, the wheat market has been insured by the local improved seed enterprise, and the farm operation of wheat has more advantages over other crops in consuming less labor for irrigation.[20] The Ethiopian

Table 1. Salient features of selected irrigation blocks for this study.

Irrigation block	Position	Potential irrigated area (ha)	Currently irrigated area (ha)	Annual released volume (m^3)	Night storage capacity (m^3)
Kudimi	Upper	373	328.88	$436*10^4$	$20.10*10^6$
Chihona	Upper	617	591.75	$641*10^4$	$35.59*10^6$
Adibera	Middle	803	699.00	$714*10^4$	NA
Tagelwedefit	Middle	616	589.00	$694*10^4$	$37.73*10^6$
Andinet	Lower	497	449.50	$501*10^4$	$40.70*10^6$
Teleta	Lower	783	760.50	$768*10^4$	$41.89*10^6$

Note: NA denotes that no data is available. Source:[23] and Koga Irrigation Development Office implementation report, 2022.

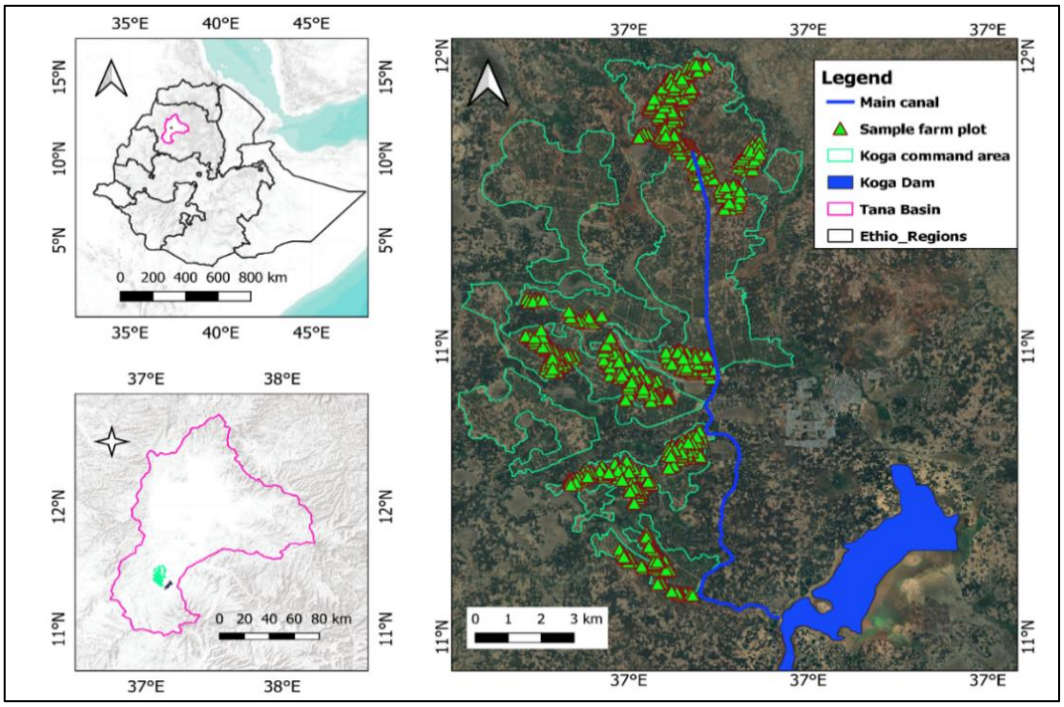

Fig. 1 The map of the study area found in the Tana basin, in the Amhara region.
source: https://www.arcgis.com/home/webmap/viewer.html?layers=c61ad8ab017d49e1a82f580ee1298931.

government also has a strategy to increase the productivity and production of wheat under dry conditions, and then the local farmers are forced to sow wheat.

To determine the start and end of the season, the data would be collected from secondary and primary sources, it is obvious that the right time of planting and harvesting in the Koga irrigation scheme is not identical and the farmers have not conducted the farm operations at the same time. However, the date of sowing and harvesting is determined by considering the peak time in which the local farmers conduct the farm operations and taken as constant over the irrigation period, as presented in Table 2.

Table 2. Start and the end of the irrigation season in the Koga irrigation scheme.

Irrigation season	Start of the season (SOS)	End of the season (EOS)	Remarks
Season_2018	01-11-2017	30-04-2018	Assume the planting and harvesting date of crops should be considered fixed
Season_2019	01-11-2018	30-04-2019	
Season_2020	01-11-2019	30-04-2020	
Season_2021	01-11-2020	30-04-2021	
Season_2022	01-11-2021	30-04-2022	

2.2 Data processing

In this project, information on climate, water, land, and intermediate data was gathered from publicly available sources (https://wapor.apps.fao.org/home/WAPOR_2/3) in December 2022 and ground data (local information). The physical data such as irrigable and irrigated land areas, total water supply, the crop calendar (the start and end of the season), and observed data were collected at the irrigation scheme through a secondary source of information, while the publicity accessible sources were downloaded from the water productivity through open-source remotely sensed data (WaPOR) portal open-access databases. This was accomplished using the graphical user interface (GUI), additionally, literature data sources were taken into account, the details were illustrated in Fig. 3.

2.3 Intermediate data

One of the recognized sources of information for evaluating and tracking water and land productivity involves the utilization of the Normalized Difference Vegetation Index (NDVI). The Normalized Difference Vegetation Index (NDVI) is a widely used remote sensing index to quantify the amount and health of vegetation in an area. In this research, this helpful remote sensing dataset is acquired from Landsat 9 satellite and estimated by using near-infrared (NIR) and red band, thus NDVI is calculated using the following formula. The specific bands and sensor characteristics used for NDVI calculation may vary depending on the satellite and sensor to be used (Table 3).

$$\mathrm{NDVI} = \frac{\mathrm{NIR-RED}}{\mathrm{NIR+RED}} = \frac{\mathrm{B5-B4}}{\mathrm{B5+B4}} \tag{1}$$

where; B5 is band five (near infrared band) and B4 is the red band which are visible bands for detection. To obtain the precise NDVI values for sample plots, the sample raster values algorithm is utilized within the QGIS platform.

Table 3. The acquisition and processing date of Landsat 9 satellite data for analysis of NDVI.

Sr. no	Sensor[1]	Date of acquisition	Date of processing	Path	Row
1	OLI/TIRS	13-Dec-21	5-Apr-23	170	052
2	OLI/TIRS	29-Dec-21	5-Mar-23	170	052
3	OLI/TIRS	14-Jan-22	5-Feb-23	170	052
4	OLI/TIRS	30-Jan-22	30-Apr-23	170	052
5	OLI/TIRS	15-Feb-22	27-Apr-23	170	052
6	OLI/TIRS	3-Mar-22	26-Apr-23	170	052
7	OLI/TIRS	19-Mar-22	24-Apr-23	170	052
8	OLI/TIRS	4-Apr-22	23-Apr-23	170	052
9	OLI/TIRS	20-Apr-22	21-Apr-23	170	052

Note: [1] OLI is operational land imagery and TIRS is the thermal infrared sensor

After obtaining satellite data for the 2022 irrigation season based on crop growth stages, we calculated the normalized difference vegetation index (NDVI) as described in Fig. 2. Both the map (left side) and the graph (right side) depict lower NDVI values at both scheme and block levels. Specifically, the scheme-level analysis revealed a minimum NDVI value, indicating water stress and inadequate irrigation water. At the block level, lower NDVI values were observed in the lower section of the scheme, indicating moisture stress. In contrast, plots in the upper and middle sections had higher NDVI values, suggesting better water availability, although water stress was not completely resolved.

2.4 WaPOR data components

The WaPOR datasets are produced by the FRAME Consortium, led by eLEAF, and comprised of the Flemish Institute for Technological Research (VITO), the International Institute for Geo-Information Science and Earth Observation at the University of Twente, and the Water Watch Foundation. The database had three different scales of spatial resolution. These are (1) at the continental (250 m resolution), (2) national (100 m resolution), and (3) irrigation scheme (30 m resolution)

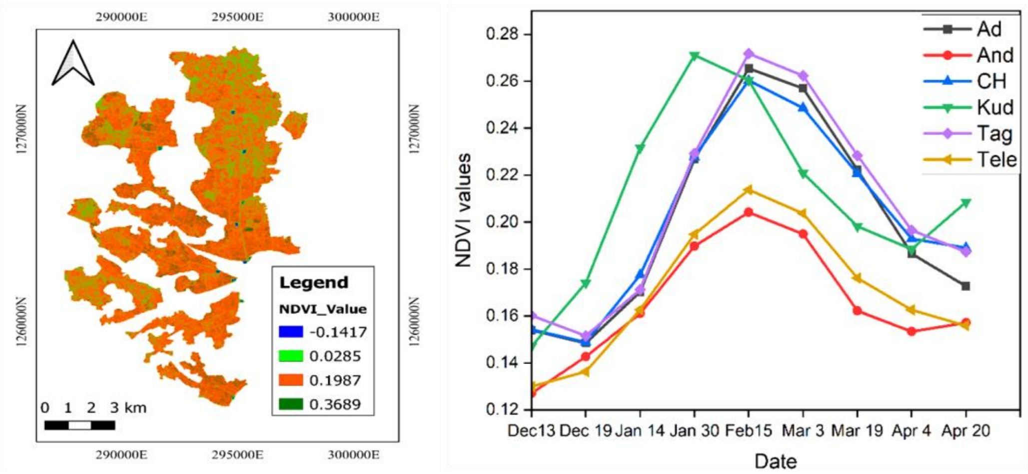

Fig. 2 NDVI values at both the scheme level (left side) and block level (right side). Here, Ad represents Adibera and stands for Andinet, CH denotes Chihona, Kud represents Kudimi, Tag stands for Tagel, and Tele corresponds to Teleta.

levels. The WaPOR database covers Africa and Near East regions in real time for the period 2009 to the present and found a way to have worldwide coverage. In this investigation, a finer resolution at 30 m and 20 km was employed and the latest version of WaPOR 2 was used (Table 4 and Fig. 3). For plots larger than 2 ha, WaPOR v2 was shown to be adequate for comparing irrigation performance indicators across plots[24] based on inter-level resolutions. Therefore, the selected farm plots for this research have an area of less than 2 ha and it is adequate for the comparison of irrigation performance indicators that would be investigated at the farm plot scale.

Table 4. Overview of datasets generated from the WaPOR portal.

Data components	Data source	Spatial resolution	Temporal resolution	Temporal coverage
Net primary production	FAO	30.00 m	Dekadal	2017 - 2022
Reference evapotranspiration	FAO	20000 m	Daily	2017-2022
Actual evapotranspiration	FAO	30.00 m	Dekadal	2017-2022
Transpiration	FAO	30.00 m	Dekadal	2017-2022
Evaporation	FAO	30.00 m	Dekadal	2017-2022

2.5 Reference evapotranspiration

Reference evapotranspiration is the climate-driven evaporation from a well-watered virtual uniform grass crop, and it is determined in various ways. In this research, the reference evapotranspiration is gained from WaPOR portal at 20 km spatial resolution.[24,25] The modern Penman-Monteith equation is used to determine the reference evapotranspiration for both sources of data. The actual evapotranspiration (Eta) is also determined and derived from the separately calculated evaporation € and transpiration (T). The calculation of the reference evapotranspiration has been split into two steps based on the FAO-56 procedure; 1) obtaining meteorological data and 2) calculating reference evapotranspiration. The latent heat flux is one of the components of energy balance equivalent to evapotranspiration and is calculated as:[26]

$$\lambda \mathrm{ET} = \frac{\Delta(\mathrm{Rn}-\mathrm{G})+\mathrm{PaCP}\left(\frac{\mathrm{es}-\mathrm{ea}}{\gamma\mathrm{a}}\right)}{\Delta+\gamma\left(1+\frac{\gamma\mathrm{s}}{\gamma\mathrm{a}}\right)} \tag{2a}$$

where: λ is the latent heat of evaporation (J/kg), E is evaporation (kg/m^2/s), T stands for transpiration (kg/m^2/s), Rn is net radiation (W/m^2), G is soil heat flux (W/m^2), Pa is air density (kg/m^3), cp is specific heat of dry air (J/kg/K), ea is actual vapor pressure of the air (Pa), es is saturated vapor pressure (Pa) that is a function of the air temperature, Δ is slope of the saturation vapor pressure. vs temperature curve (Pa/K), γ is psychrometric constant (Pa/K), ra is aerodynamic resistance (s/m), rs is bulk surface resistance (s/m), α_0 is the surface albedo, and Rs is incoming solar radiation (W/m^2).

$$\mathrm{ETo} = \frac{0.408\Delta(\mathrm{Rn}-\mathrm{G})+\gamma\left(\frac{900}{\mathrm{T}+273}\right)\mu2(\mathrm{es}-\mathrm{ea})}{\Delta+\gamma(1+0.34\mathrm{u}2)} \tag{2b}$$

2.6 Actual evapotranspiration

Evaporation and transpiration occur simultaneously, and there is no easy way of distinguishing between the two processes (evaporation and transpiration). The evaporation is determined by a fraction of radiation reaching the soil surface, and the transpiration is based on the development of crop growth. At sowing, nearly 100% of ET comes from evaporation, while at full crop cover, more than 90% of ET comes from transpiration.[27] In the hydrological cycle, evapotranspiration (ET) is a significant parameter that, along with precipitation, regulates the availability of water for irrigation and other water management practices.[28] Typically, the largest and most important flow path in a water balance is actual evapotranspiration from irrigated lands. Furthermore, actual evapotranspiration can vary greatly in both time and space, making it difficult to obtain a representative measurement or estimate. It is also influenced by human-made and natural processes. Thus, most researchers calculate potential rather than actual evapotranspiration. The seasonal water

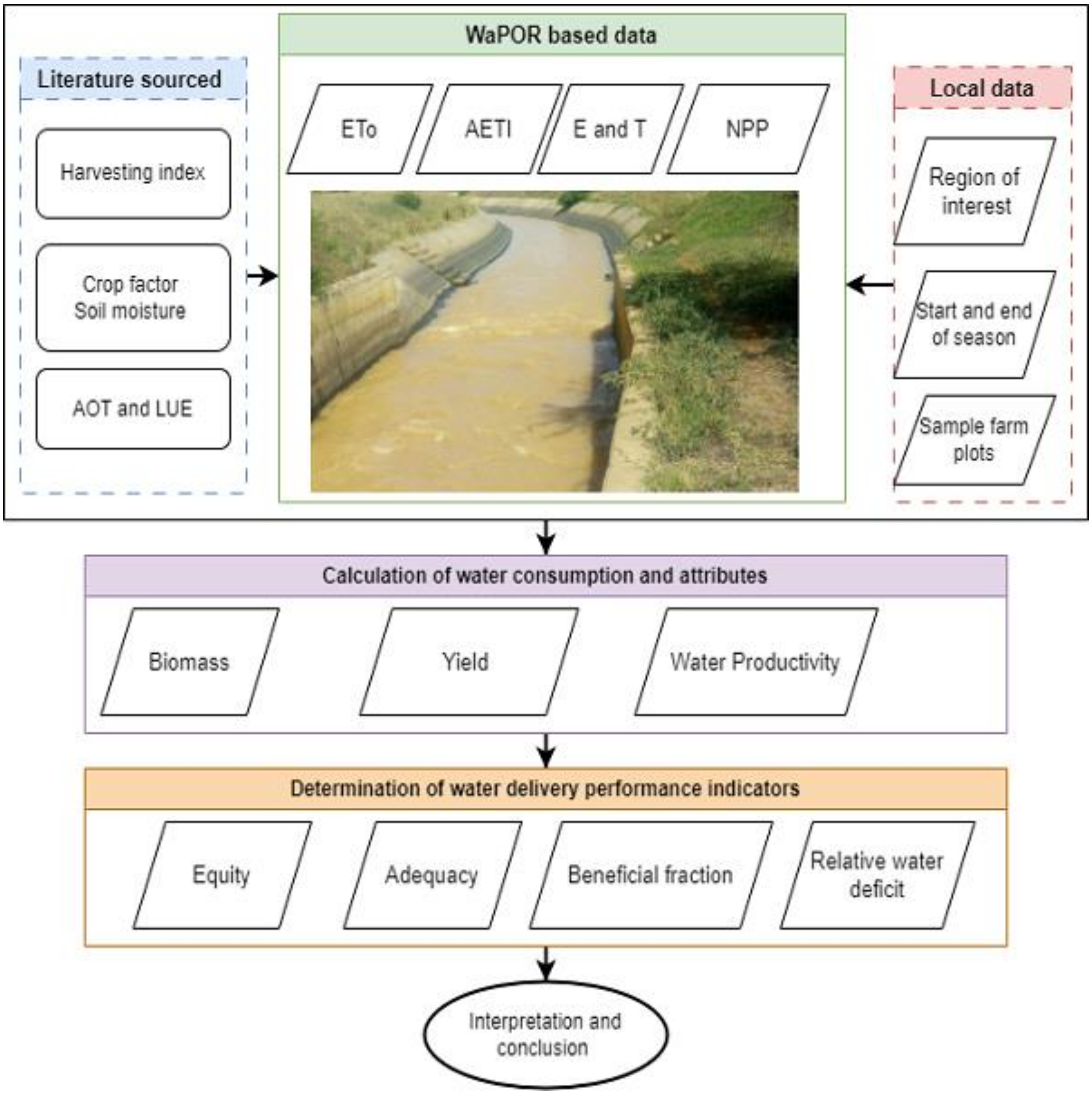

Fig. 3 The simplified framework and order of the performed activities in this research.

consumption is calculated by aggregating the monthly values (equation 3).

$$\mathrm{ETa,s} = \sum_{\mathrm{SOS}}^{\mathrm{EOS}} \mathrm{ETa} \tag{3}$$

where ETa is the actual evapotranspiration that includes evapotranspiration and interception, ETa, s is seasonal actual evapotranspiration in mm/season, and SOS and EOS are the starting and ending of the crop season.

Evapotranspiration plays a great role in determining the exchanges of energy and mass between the states such as hydrosphere, atmosphere, and biospheres.[29] The actual evapotranspiration and evaporative fraction were calculated, and the data were overlain with a digital map of all distributaries. Actual evapotranspiration was the basis for equity and evaporative fraction for adequacy and reliability. There are different methods to compute evapotranspiration (ET), in this research, the actual evapotranspiration is estimated from the remotely sensed WaPOR dataset, while the potential evapotranspiration is calculated using the meteorological data method.

$$\mathrm{ETc} = \mathrm{ETo} * \mathrm{Kc} \tag{4}$$

where Kc =crop coefficients that relate ETo to ET

Because of the limitation of data in the WaPOR dataset, there is no sufficient information on the crop growth stage to consider the kc at a finer temporal resolution. The sole kc method is used rather than the dual crop coefficient method for this research.

2.7 Biomass production

An ecosystem's basic unit, net primary production (NPP) expresses how photosynthesis transforms carbon dioxide into biomass. Daily incoming solar radiation, temperature (Tmin/Tmax), dekadal fAPAR, soil moisture stress, and seasonal land cover were used to calculate NPP. The pixel values are more suitable for measuring dry matter production since they indicate the average daily NPP in gC/m^2/day for the given decade (DMP) and a pixel value of the downloaded data must be divided by a conversion factor of one thousand (1000). To convert the net primary production to dry matter production (DMP), a constant scaling factor of 0.45 gC/m^2 DM in kg DM $ha^{-1}day^{-1}$ is used[30] and the total biomass production (TBP) is estimated using equation (4a).

$$\mathrm{TBP}\left(\frac{\mathrm{kgDM}}{\mathrm{ha.day}}\right) = 22.22 * \mathrm{NPP} \tag{5a}$$

$$\mathrm{AGBP}\left(\frac{\mathrm{kgDM}}{\mathrm{ha.day}}\right) = 0.65 * \mathrm{TBP} \tag{5b}$$

where NPP is net primary production (gC $m^{-2}day^{-1}$), TBP is total biomass production (kg $ha^{-1}day^{-1}$), AGBP is above-ground biomass production (kg $ha^{-1}day^{-1}$), 0.65 is a conversion factor used to convert the total biomass production to above-ground biomass production, and 22.22 is a conversion fraction which converts the net primary production into dry matter productivity (below and above ground dry biomass).

After harmonizing the required data within the specific region of interest and spatial resolution, the biomass in ton per hectare/ season is estimated using total biomass production, above-ground biomass to total biomass production ratio (AOT), light use efficiency correction factor, and moisture content of the fresh biomass as shown the given below.[31,32]

$$\mathrm{B} = \frac{\mathrm{AOT}*\mathrm{fc}*\mathrm{NPP}*22.22}{1000(1-\theta)} \tag{6}$$

where θ is moisture content, fc is light use efficiency correction factor (both the parameters taken from literature) as explained in Table 5. The light use efficiency correction factor is determined depending on the crops' photosynthesis mechanism as the crops are categorized into C3 and C4 crops, which are the photosynthetic pathways the plants use to convert light energy into chemical energy through photosynthesis. In this study, the inputs total biomass production and harvesting index (HI) is used to compute the yield of the crop.

$$\mathrm{Yield} \ = \mathrm{B} * \mathrm{HI} \tag{7}$$

Table 5. Parameters used to analyze biomass and yield of the crops retrieved from the literature.

Parameter Definition	Symbol	Value	Reference
Above ground to total biomass ratio	AOT	0.85	[25]
Light use efficiency correction factor	fc	1.00	[25]
Harvesting index	HI	0.48	[25]
Moisture content ratio	θ	0.15	[25]

2.7.1 Biomass Water Productivity

The quantity of output (biomass production) divided by the total amount of water utilized over a specific period is known as gross biomass water productivity.[33] By connecting the generation of biomass to overall evaporation (the sum of soil evaporation, canopy transpiration, and interception). This indicator helps to understand how vegetation growth affects consumptive water use and, in turn, the water balance in a specific domain. The gross biomass water productivity is calculated as follows:

$$\mathrm{GBWP} = \frac{22.22*\mathrm{NPP}}{10*\mathrm{ETa}} \tag{8}$$

where NPP = Seasonal net primary production in gCm^{-2} and converted into total biomass production (kgDM $ha^{-1}day^{-1}$) using a conversion factor 22.22. ETa = actual evapotranspiration, which is the sum of evaporation, interception, and transpiration (mm), and 10 is a factor used to convert mm into m^3.

The amount of output (total biomass production) concerning the amount of water used beneficially (via canopy transpiration) throughout the year is expressed as net biomass water productivity. At the country level, net biomass water productivity is calculated and made available through WaPOR on a seasonal basis at levels 2 and level 3. For this study, level 3 data availability is used for analysis. Total biomass production, transpiration, and, phenology are the inputs needed to compute net biomass water productivity. Thus, net biomass water productivity would be estimated using the formula below.

$$\mathrm{NBWP} = \frac{22.22*\mathrm{NPP}}{10*\mathrm{T}} \tag{9}$$

where NBWP = net biomass water productivity and T is transpiration from the crop

2.7.2 Crop Water Productivity

Gross crop water productivity is the ratio of crop output to total water consumption over a specific period.[33,34] In general, crop water productivity is expressed in terms of transpiration; WP(T), and evapotranspiration; WP (ET). Based on the availability of information unique to a given crop and the possibility of user-defined aggregation, GCWP is calculated by WaPOR on a seasonal basis at level 3. The above-ground biomass production, Phenology, actual evapotranspiration, and reference evapotranspiration datasets obtained from WaPOR were used to determine water productivity. The gross and net crop water productivity is calculated by applying the following equation.

$$\mathrm{WP(ET)} = \frac{\mathrm{TBP}*\mathrm{HI}*\mathrm{AOT}\ (1-\theta)}{\mathrm{ETa}} = \frac{\mathrm{Yield}}{\mathrm{ETa}} \tag{10a}$$

$$\mathrm{WP(T)} = \frac{\mathrm{TBP}*\mathrm{HI}*\mathrm{AOT}\ (1-\theta)}{\mathrm{T}} = \frac{\mathrm{Yield}}{\mathrm{T}} \tag{10b}$$

where AOT = is the ratio between AGBP to TBP, θ is the moisture content in the harvested product, both values are found in the literature for most common crops and would make available through the WaPOR portal, and HI denotes harvesting index.

2.7.3 Delivery Performance Indicators

For the investigation of the irrigation system performance, researchers use different indicators. For instance, the overall consumed ratio,[35] crop water deficit,[36] relative water supply,[37] relative evapotranspiration,[38,39] delivery performance ratio, drainage ratio and depleted fraction,[39] and equity and reliability,[40-42] based on ground data and open access data availability. For this research equity, adequacy, relative water deficit, beneficial fraction, and water productivity were used as the basic criteria for the assessment of the irrigation performance of the irrigation scheme. The selection of performance indicators was mainly due to the requirement of remote sensing-based data rather than field data which faced data scarcity and the cost-effectiveness and accuracy required.[43]

Equity is an extremely important aspect of irrigation management which deals with the spatial distribution of water from the system manager's point of for a large supply-based irrigation system.[43] But in areas like the Koga irrigation scheme, suffering multilateral issues (poor water management, imbalance water distribution, and poor hydro metrological network), equity in water consumption is very crucial at the system level and thus computed from remote sense estimates of actual evapotranspiration (ETa). The coefficient of variation (CV) of actual evapotranspiration (ETa) would be used as the key parameter to assess equity across the irrigation scheme in the irrigation season of 2018 to 2022. The CV used here is a measure of variability determined as the ratio of the standard deviation to the mean monthly actual evapotranspiration (ETa).

$$\mathrm{CV} = \frac{\text{SD of ETa}}{\text{mean of ETa}} \tag{11}$$

Adequacy is a measure that reveals if the required amount of water is adequately supplied to crops under irrigation.[44] It is a measure of the ability of an irrigation system to meet targeted deliveries in terms of quantity. Adequacy is also expressed in terms of relative evapotranspiration (RET). This indicator is used for measuring irrigation adequacy to investigate the presence of water shortages and evaluate the sufficiency of water delivery to a known command area.[37] Relative evapotranspiration is known to be a reliable measure of plant available soil water and it is proportional to plant growth.[43] The RET is calculated as the ratio of ETa to ETP and ETP is the product of reference evapotranspiration and crop factor.

$$\mathrm{RET} = \frac{\mathrm{ETa}}{\mathrm{ETo} * \mathrm{Kc}} \tag{12}$$

The adequacy is a crop-specific performance indicator thus, the particular parameters required to be considered in this study are listed in Table 5 and the average kc value is used to compute the adequacy of the irrigation scheme as shown below (Table 6).

Table 6. The crop factor values of wheat were retrieved from the literature.

Growth stage	FAO[20]			
	kc	day	kc	day
Initial	0.35	20	0.70	15
Development	0.75	25	0.93	25
Mid-season	1.15	60	1.15	50
Late season	0.45	30	0.32	30
Total	2.70	135	3.10	120

Relative water deficit refers to the amount of water that is available relative to the demand or the requirement for that water. The relative water deficit exists when the water demand exceeds the availability of supply and occurs due to a variety of factors. In this case, the relative water deficit is computed by equation (13).

$$\mathrm{RWD} = 1 - \frac{\mathrm{ETa}}{\mathrm{ETx}} \tag{13}$$

where ETx is the maximum crop evapotranspiration (ET) and it is equal to the 99 percentiles of actual evapotranspiration (Eta).

In the context of irrigation performance indicators, the beneficial fraction refers to the portion of the water that is effectively used by crops and contributes to their growth compared to the total amount of water applied. It also evaluates the effectiveness of the irrigation system in delivering water to plants.

The beneficial fraction is estimated as the ratio of the water that is consumed as actual transpiration (Ta) to overall field water consumption (Eta). It, therefore, shows the efficiency of on-farm water and agronomic practices in the use of water for crop growth.

$$\text{Beneficial fraction} = \frac{\mathrm{Ta}}{\mathrm{Eta}} \tag{14}$$

3. Results and discussion

3.1 Seasonal actual evapotranspiration

The descriptive statistics of the actual evapotranspiration and transpiration for each irrigation season are presented in Table 7. The results revealed that actual evapotranspiration has increased over the irrigation season. It indicated that the total amount of water lost through the combined process of evaporation from the soil and transpiration from the plant has risen during the irrigation period due to climatic factors. The mean value of ETa for season_2018 is smaller than the other seasons and the deviation is due to water scarcity. Since the actual evapotranspiration is a combination of evaporation from the soil surface and transpiration from the crop canopy, the minimum value is not zero, While the transpiration has a minimum value of zero because as the start of the crop season, transpiration has never occurred.

Table 7. Descriptive statistics of actual evapotranspiration and transpiration (mm/season).

Growing season	Minimum	Maximum	Mean	Median
Actual evapotranspiration				
2018	164	947	439	570
2019	201	1060	562	570
2020	186	1063	556	564
2021	198	1091	557	560
2022	177	1077	594	604
Transpiration				
2018	0.0	858	326	314
2019	0.0	964	432	438
2020	0.0	970	426	432
2021	0.0	956	423	424
2022	0.0	960	439	443

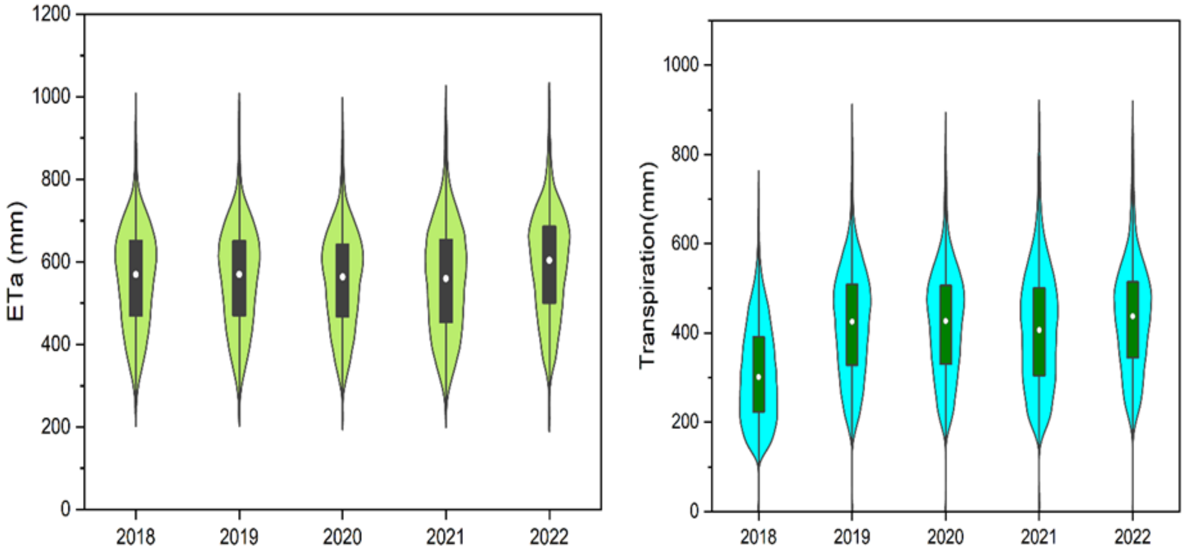

Fig. 4 The Violin plot showing the actual evapotranspiration (left side) and transpiration (right side); the hole denotes the median value, the black and the green box indicates 25-75% of the data, and the whisker line shows the value range within 1.5IQR (interquartile range)

The actual evapotranspiration shows significant variation and a higher standard deviation within each irrigation period. ETa has a difference of less than 122 mm within the irrigation season and the values increased from season to season, which assumes that the covered area of the scheme has increased over the season. The coefficient of variation within the pixel values of season_2018 is larger than the other irrigation periods and shows the same trend with other findings[24] carried out in this scheme with consideration of three levels of spatial resolutions.

According to Table 7 and Fig. 4, the actual evapotranspiration median value ranges from 570 to 604 mm per season, while the actual transpiration median value ranges from 314 to 443 mm per season over the irrigation season spanning from 2018 to 2022. This result implies that between 36% and 82% of actual evapotranspiration comes from canopy transpiration, while the remainder is due to surface evaporation and interception.

The boxplot showed that the computed actual evapotranspiration at the lower, middle, and upper regions of the irrigation scheme. Fig. 5 illustrates a consistent pattern in both the observed and estimated values of evapotranspiration. Nevertheless, the WaPOR product displays outlier values, suggesting significant disparities in water distribution within the irrigation scheme. This results in an underestimation of actual evapotranspiration when compared to ground information and the outliers in remotely sensed products occurred due to natural variability. Furthermore, when examining evapotranspiration at a finer resolution, we observe

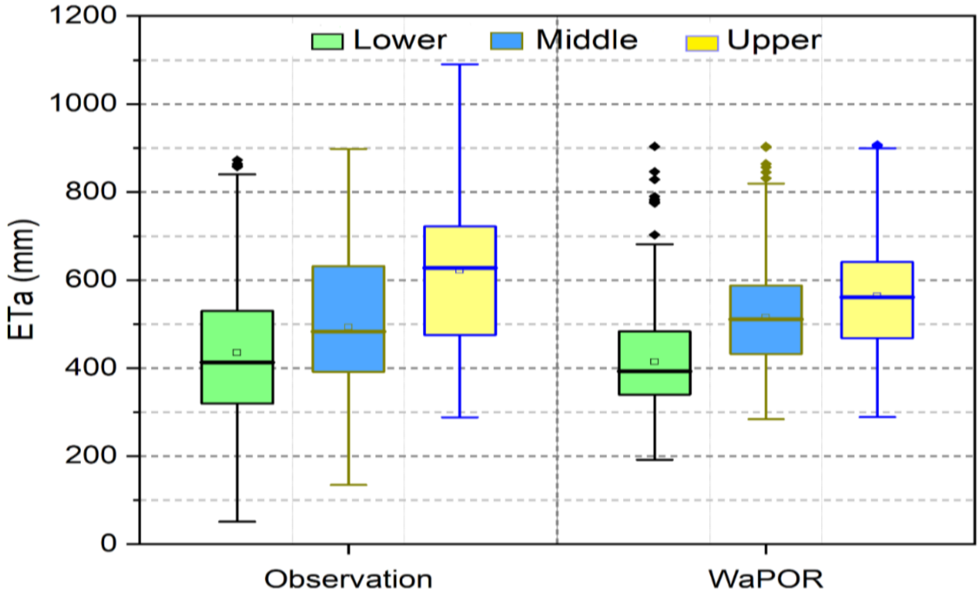

Fig. 5 Comparison of observed and WaPOR estimated actual evapotranspiration in the 2018 irrigation season at various sections of the Koga irrigation scheme.

minimal and substantial variations among the fields, due to the diverse range of crops cultivated in the irrigation scheme.

The irrigation block Kudimi had the highest median value of actual evapotranspiration, followed by the irrigation blocks Chihona and Tagel (Fig. 6). This can be attributed to their proximity to a water supply. On the other hand, the irrigation blocks at the tail of the scheme (Teleta and Andinet) struggled with a lack of water supply, which left some farmland unattended and had the lowest mean and median value of actual evapotranspiration. The other researcher also discovered that the farmers' fields located at the lower part of the scheme were subject to a water shortage during irrigation time.[20,45] The actual evapotranspiration fluctuates across the lower, middle, and upper fields of the scheme, contingent upon the location of the farmers' plots. As illustrated in Fig. 6, the agricultural fields situated in the lower half of the irrigation scheme exhibit the least actual evapotranspiration.

3.2 Biomass and yield

Crop yield and biomass can be estimated using the WaPOR portal products and literature values from different research findings and FAO papers. The analysis results of biomass and yield of wheat are presented in Table 8. For all irrigation periods, the level of dataset variability within the pixel is larger. The CV can, however, be larger for crops with greater biomass and production variability because of fluctuations in agronomic techniques and practices, soil moisture, nutrient availability, and weather patterns. The predicted yield and biomass of wheat are lower than the values reported in the previous research,[46] where they found that wheat had a maximum biomass of 10.9 t ha^{-1} and a yield of 4.6 t ha^{-1} in plot-level experiments. Despite this, using the open-access remote sensing data portal to compute yield and biomass remains the best option for gaining insights at large-scale levels. In this case, we used the Koga irrigation scheme for our analysis.

Table 8. The WaPOR-based biomass and yield of wheat in the irrigation scheme.

Irrigation period	Biomass (t ha^{-1})	CV (%)	Yield (t ha^{-1})	CV (%)
Season_2018	5.9	40	2.8	41
Season_2019	7.2	32	3.5	33
Season_2020	7.6	31	3.7	31
Season_2021	7.2	36	3.4	36
Season_ 2022	7.6	33	3.7	32

Note: CV = coefficient of variation at each irrigation season.

The scatter plot shows the strong relationship between biomass and actual evapotranspiration (Fig. 7). The linear relationship between biomass and evapotranspiration indicates a good agreement with other research findings investigating sugarcane production under different irrigation types.[47,48] A positive correlation is found when comparing the two metrics, showing distinct and consistent trends. Despite the similarity in seasonal patterns, some values appear as outliers. Additionally, the lack of results displayed by the pixels suggests that this area might be a walkway, road, barren ground, or an area without vegetation, making it difficult to pinpoint the exact location.

The correlation coefficient of actual evapotranspiration versus biomass is less than the correlation coefficient of

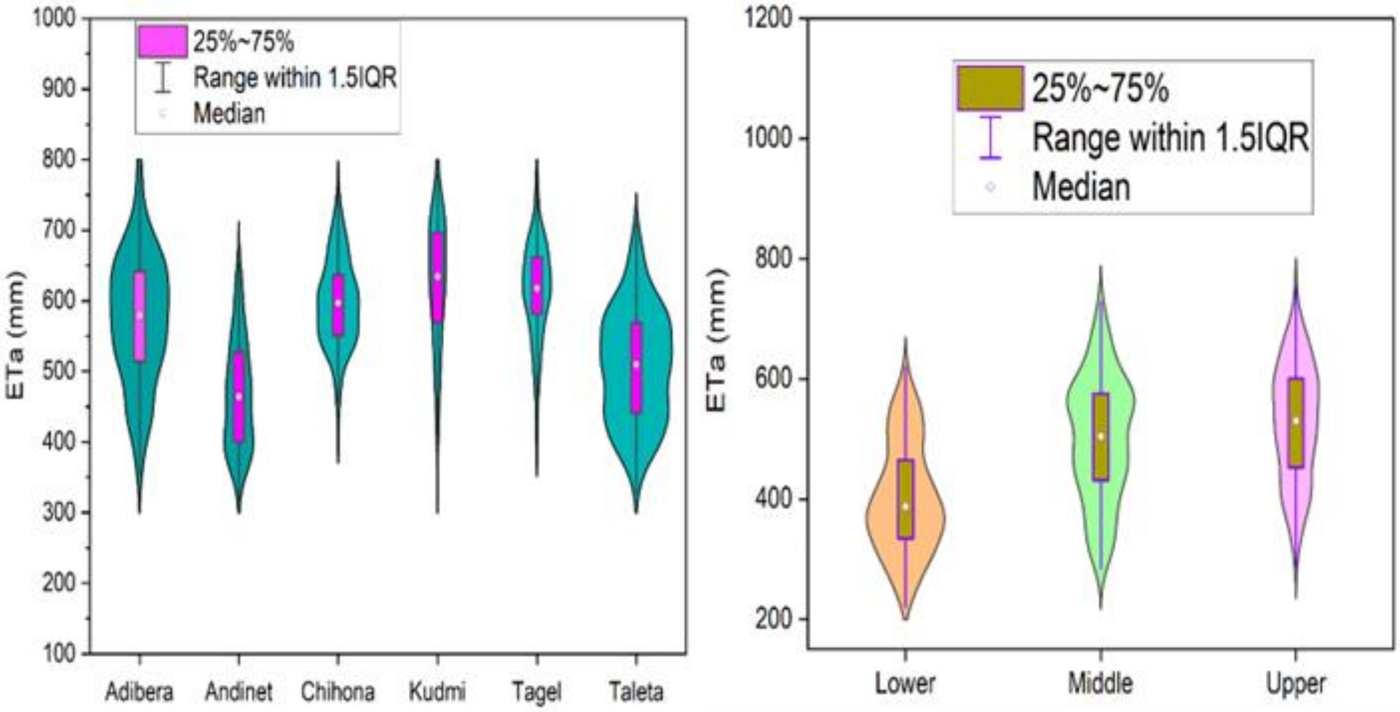

Fig. 6 The seasonal water consumption alongside the irrigation blocks (left side) and upper, middle, and lower (right side) sections of the scheme over the irrigation period.

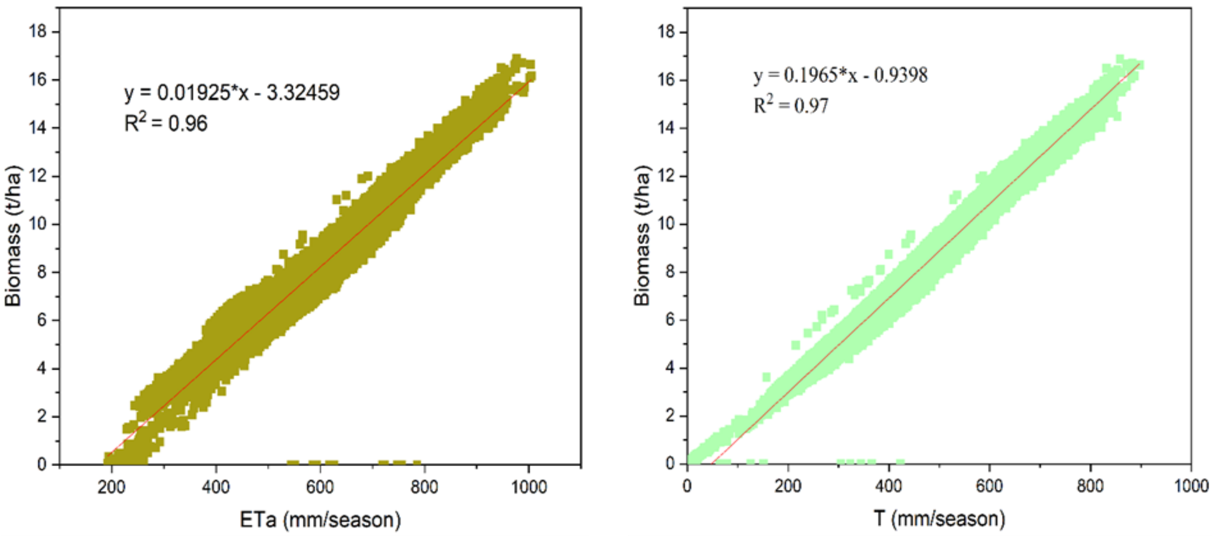

Fig. 7 Scatter plots of the seasonal biomass versus actual evapotranspiration (left side) and biomass versus transpiration (right side) from the 2018-2022 irrigation season.

transpiration versus biomass (Fig. 7). This indicates the accurate estimation of transpiration and surface evaporation at level three spatial resolution in WaPOR.

Table 8 displays the wheat yield, while Fig. 8 illustrates the spatial distribution of yield and crop water productivity across the five irrigation growing cycles within the Koga irrigation project. The biomass can be found in the WaPOR dataset and the harvesting index can be sourced from the literature. The WaPOR dataset provides information on the biomass and does not directly give the yield. The average wheat yield determined by this analysis is lower than the results of earlier research reported by Ref. [49] who found that 5.5 t ha^{-1} wheat yield and higher than the maximum wheat yield (2.85 t ha^{-1}, 2.8 t ha^{-1}) reported by Ref. [45,50] took place under various irrigation water management strategies at similar irrigation agroecology. The grain yield and water productivity of wheat were tracked spatially and temporally across a five-year irrigation season. Spatially, the average yield and water productivity were found between 2-8 t ha^{-1} and 0.35-1.42 kg m^{-3}, respectively. The spatial water productivity of this study was found within the average values reported by Ref. [51]; which ranged between 0.2 and 1.80 kg m^{-3} and it was also discovered in the global range as well (0.62 to 2.0 kgm^{-3}).[42] Demonstrating that there is a lot of room for improvement. The fields at the lower reach experience water productivity gaps and exhibit a lower production of wheat (Fig. 8).

3.3 Water productivity

The analysis of water productivity is performed after the quantification of seasonal water consumption, transpiration, biomass, and crop yield. In this research, the water

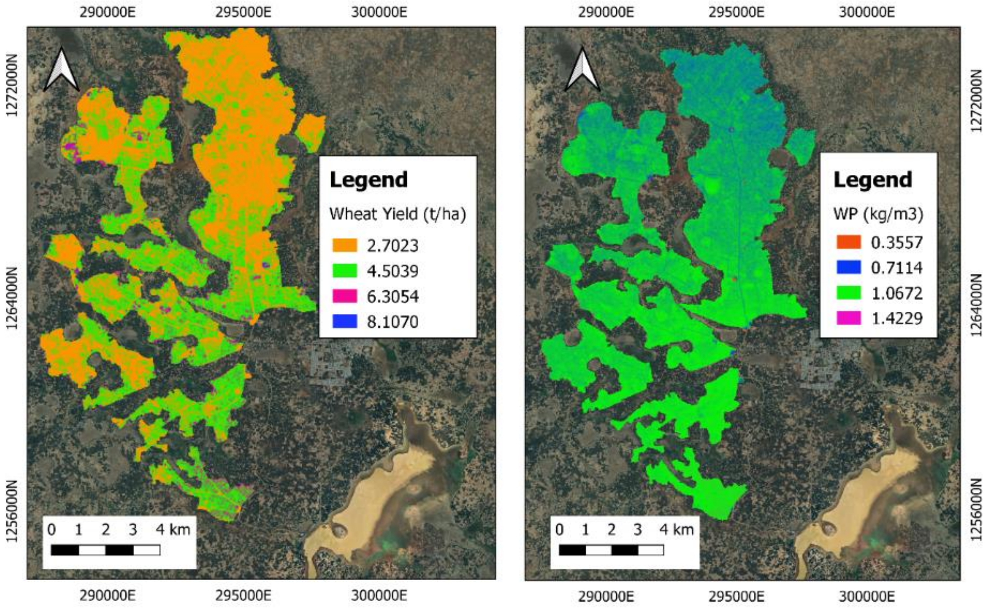

Fig. 8 The spatial variation of wheat yield and crop water productivity across the Koga irrigation scheme.

productivity is considered as biomass water productivity and crop water productivity in line with actual evapotranspiration and transpiration respectively.

3.3.1 Biomass Water Productivity

Per the WaPOR version 2 manual,[25] the analysis results for gross and net biomass water productivity fall within the accepted range of 0 to 6 kg m^{-3}. In this study, the average value of the gross productivity is close to the research reported by Ref. [24]. However, some outliers strongly suggest variation in biomass production and low water consumption due to poor distribution of irrigation water among users (Fig. 9). In the Koga irrigation scheme, diverse practices and crop management activities are performed. This led to both exceptionally low and high biomass water productivity. The value zero indicates the command area is not fully covered by the crops, and there are open paths between fields for farming operations and uncultivated lands (Fig. 9). Particularly, the net biomass productivity depicts an insight into the cultivated crops and the scheme water productivity circumstances.

3.3.2 Crop Water Productivity

Throughout the irrigation growing season, the average gross crop water productivity ranged from 0.78 to 1.34 kg m^{-3} and average net crop water productivity varied from 0.80 to 1.25 kg m^{-3} (Table 9), those results were comparable with the research investigations conducted on mapping of water productivity.[51] Overall, the net crop water productivity is less than the gross crop water productivity, this implies the need for agricultural water management improvement and efforts to improve water use efficiency in this scheme.

Upon analyzing the results, it becomes evident that the 2019 irrigation season consistently exhibits the highest values for gross crop water productivity within the range of 0.5 to 1.0 kg m^{-3}. Conversely, the irrigation seasons of 2018, 2020, 2021, and 2022 exhibit similar trends in gross crop water productivity. In contrast, the growing seasons from 2020 to 2022 demonstrate the lowest values for net crop water productivity, falling within the range of 0.5 to 1.0 kg m^{-3}. Meanwhile, the 2018 and 2019 seasons consistently display the highest net crop water productivity, ranging between 1.0 and 2 kg m^{-3}.

3.4 Performance indicators in space and time

3.4.1 Equity

The mean seasonal variation of equity is calculated as the ratio of standard deviation and mean of seasonal actual evapotranspiration, and this is presented in Fig. 10 and Table 10. According to the performance indicator standards, a CV of28 % in 2018 has indicated the highest heterogeneity in water consumption compared to a CV of 24 % in 2021 and a CV of 22 % in the growing seasons of 2019, 2020, and 2022. The overall variation of seasonal water consumption among the users indicates a lower level of heterogeneity, suggesting a fair distribution of water among the irrigated fields. However, this does not imply that the water distribution gap has been fully addressed. The inter-seasonal trend of water distribution is better as compared to the research findings of Ref. [24]. The results of the analysis also aligned with Ref. [52] research investigations. Their findings revealed that equity in the irrigation scheme was fair during the 2017 and 2018 irrigation seasons, but it became unfair and poor in the 2019 irrigation season. Thus, the evenness of water distribution among the irrigators is under question in the Koga irrigation scheme.

Water is not evenly distributed among the irrigated fields, and different fields use different amounts of irrigation water on dekadal and a monthly time scale (Fig. 10). Due to the significant volume of irrigation water that is initially released for land preparation at the beginning of irrigation, water consumption is evenly distributed among users during the initial stages of farm operations. Consequently, water scarcity becomes apparent during the development and late-season

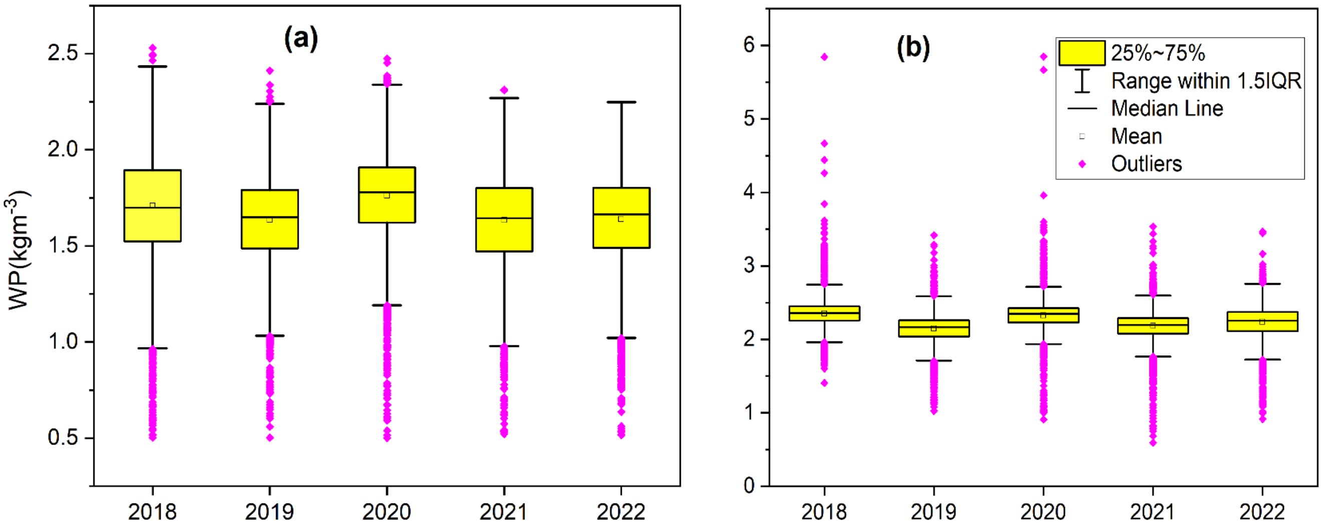

Fig. 9 Gross biomass water productivity (a) and net biomass water productivity (b) over the irrigation period and across the irrigation scheme.

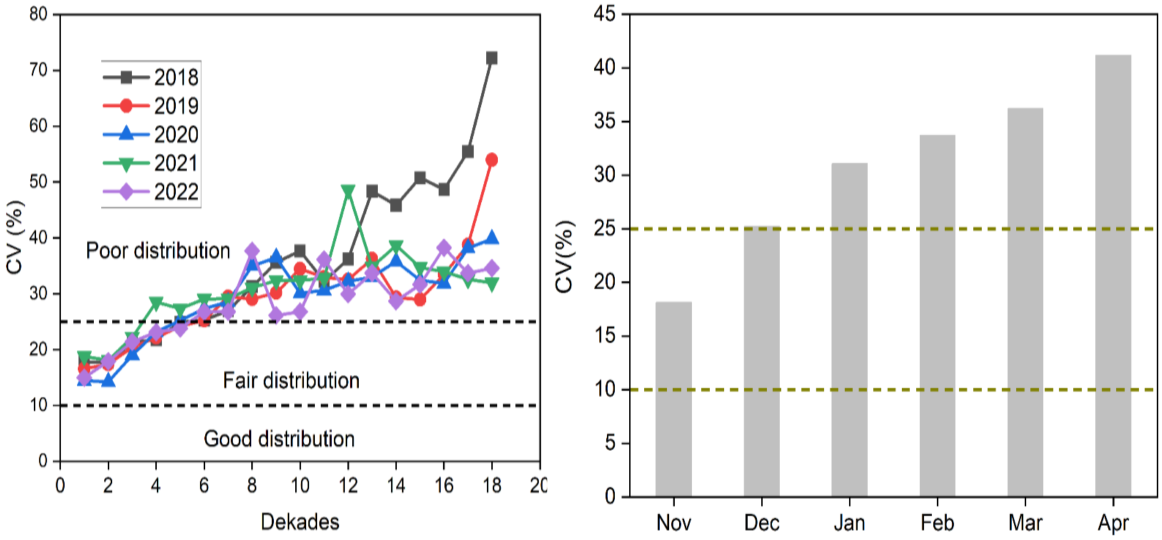

Fig. 10 Tracking of the equitability of water distribution by considering the dekadal (left side) and monthly based (right side) over the irrigation period.

Table 9. Descriptive statistics of gross and net crop water productivity of wheat over the growing period 2018 to 2022.

Irrigation season	GCWP[1] (kg m^{-3})				NCWP[2] (kg m^{-3})			
	Mean	Max.	Median	CV (%)	Mean	Max.	Median	CV (%)
2018	1.30	1.93	1.29	15	1.25	1.7	1.27	14
2019	0.78	1.25	0.79	7.7	1.64	2.6	1.65	7.0
2020	1.34	1.89	1.36	13	0.80	1.3	0.81	7.5
2021	1.25	1.77	1.26	14	0.80	1.3	0.81	7.5
2022	1.25	1.72	1.27	14	0.82	2.0	0.83	8.5

Note: [1] gross crop water productivity (the ratio of yield and actual evapotranspiration) and [2] net crop water productivity (yield divided by actual transpiration).

growth stages. As the irrigated area becomes fully covered and the crops advance in growth stages, the demand for water increases leading to competition among users. As a result, water distribution fairness among the fields diminishes during this period, as shown in Fig. 10. The water demand of the irrigators increases during the crop development stage leading to conflict among the farmers.

3.4.2 Relative evapotranspiration

The five-season average adequacy varies spatially across the Koga irrigation scheme, with noticeable differences between the irrigated fields located in the lower reaches compared to those in the middle and upper regions of the scheme. Fig. 11 indicates the highest mean value of adequacy for the 2022 irrigation season (0.86) followed by the 2019 to 2021 irrigation season (0.81), which falls in the acceptable range of adequacy and indicates sufficient water supply throughout the scheme. This result is similar to those attained by Ref. [53]. On the other hand, the lowest level of adequacy (0.66) was obtained in the 2018 irrigation season. The relative evapotranspiration is higher in the fields located at the upper section scheme than in irrigated fields found in the middle and lower portions of the scheme. For the five-irrigation season, the tail section of the scheme showed the lowest value of adequacy (Fig. 10). This is an indication; that the adequacy of water can be affected by the reason general water availability; *i.e.*, the proximity of the irrigated field to the water source affects the relative evapotranspiration.

As indicated in Table 10, the Koga irrigation scheme continues to face challenges concerning water sufficiency and the extent of water deficit, which hinder improvements in irrigation water distribution efficiency and the overall irrigation system's effectiveness. Both performance metrics, adequacy, and relative water deficit, were identified as falling below acceptable levels or the predefined thresholds.

Table 10. The average values of the seasonal water delivery performance indicators were computed from the WaPOR dataset.

Growing season	Adequacy	Equity	Beneficial fraction	RWD
2018	0.66	0.28	0.72	0.23
2019	0.81	0.22	0.76	0.35
2020	0.81	0.22	0.75	0.35
2021	0.81	0.24	0.74	0.38
2022	0.86	0.22	0.73	0.34
Overall mean	0.79	0.24	0.74	0.33
Decision	Poor	Fair	Acceptable	Poor

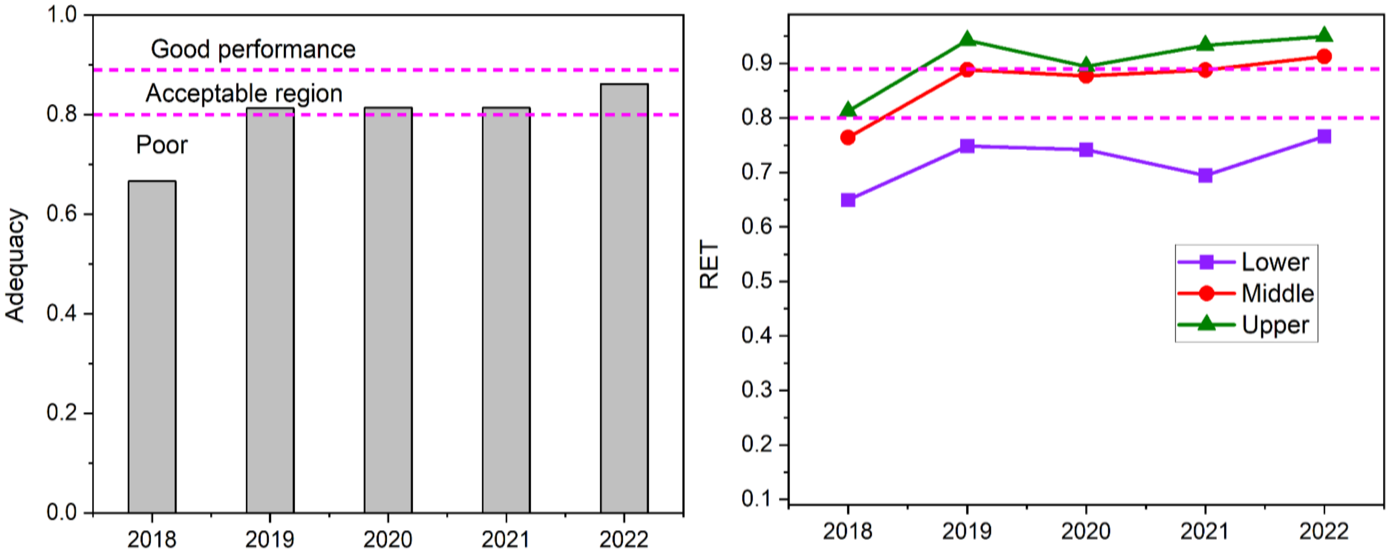

Fig. 11 The adequacy of the five-irrigation season (left side) and the irrigation field categorized by the reach (right side) in the Koga irrigation scheme.

Consequently, these metrics serve as indicators of soil moisture stress conditions within the crop root zone and signify a reduction in water uptake by the roots for crop transpiration, commonly referred to as transpiration deficit.

3.4.3 Relative water deficit

The relative water deficit is presented in Fig. 12b, Fig. 13a, and Table 10. According to the result of the analysis, the irrigated crops in the scheme are exposed to water stress and the values indicated that the mild and severe water stress are the critical conditions in the scheme. Particularly, the crops cultivated at the lower portions of the scheme were subjected to water stress as compared to the upper reaches of the scheme (Fig. 12b), and the water supply relative to the crop water need is low. As indicated in Fig. 13a, the severity of the water stress increases from the upper to lower regions of the irrigation scheme for all irrigation seasons and this points out that the Koga irrigation scheme has irrigation water management gaps. A high relative water deficit indicates that there is not enough water available to meet the crop's requirements in the scheme.

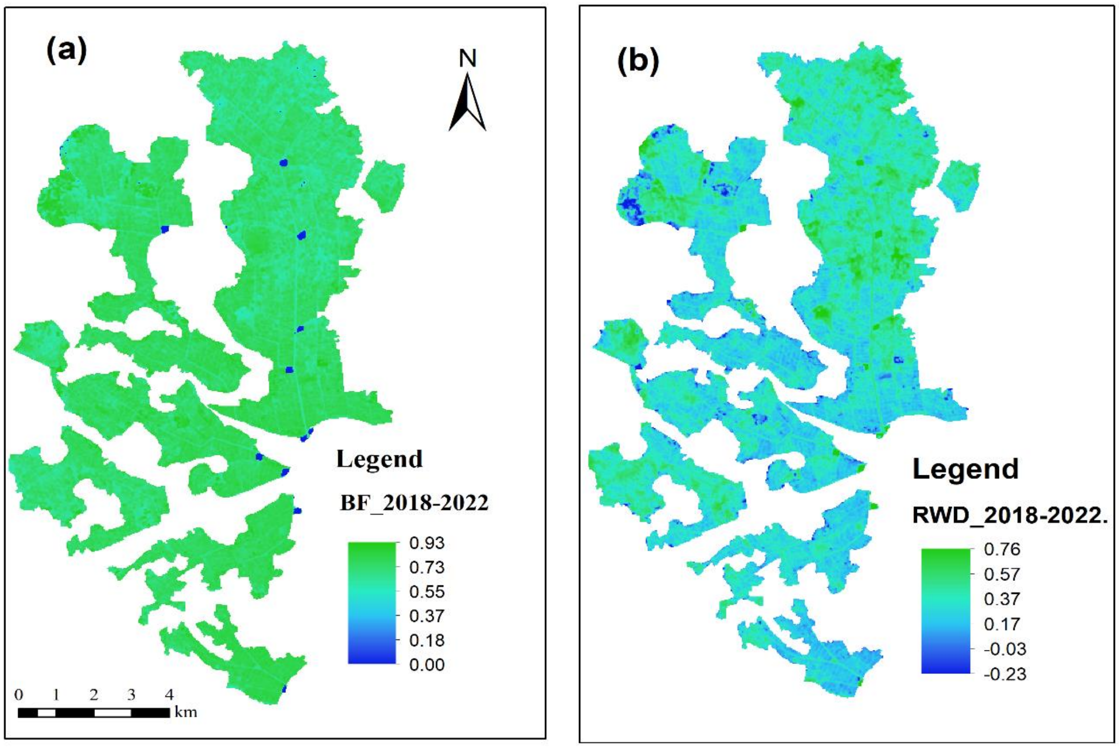

Fig. 12 The spatial variation of (a) beneficial fraction (BF) and (b) relative water deficit (RWD) across the growing season from 2018-2022

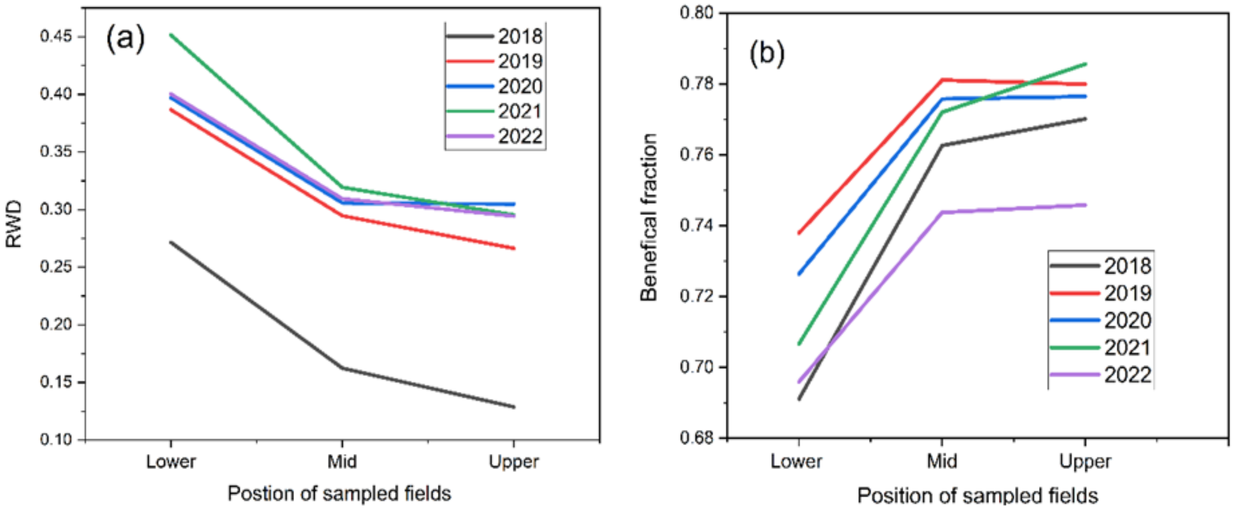

Fig. 13 The trends of a relative water deficit (a) and a beneficial fraction (b) based on the extent of agricultural fields.

3.4.4 Beneficial fraction

Figures 12a and 13b show the beneficial fraction in the irrigation scheme. The result that is displayed demonstrates that a greater beneficial fraction is present. This shows that a higher proportion of the available applied water is being utilized effectively by the crops. Based on the alignment of the irrigation scheme, fields located at the upper reach have a higher percentage of beneficial fraction followed by the middle section of the scheme while lower regions of the command area have a lower percentage of beneficial fraction (Fig. 13b). Even though the beneficial proportion is higher, the irrigation system still faces water stress and the availability of soil moisture in the crop root zone is insufficient. The spatial distribution of information on the beneficial fraction can significantly show the availability of applied water which is efficiently used by the crops to gain the highest possible yield in the scheme (Fig. 13).

4. Conclusion

Currently, there is a capacity to update and assess water consumption monitor the irrigation scheme performance over time and space, and use available open-access databases at finer resolutions to enhance agricultural water management of the irrigation scheme. The goal of this study is to assess water consumption and water delivery performance indicators such as productivity, adequacy, equity, beneficial fraction, and relative water deficit using open-access remote sensing data in the Koga irrigation project. The computed actual evapotranspiration is higher in the upper reach and lower in the tail reach of the Koga irrigation scheme, while in the middle section, it falls within an intermediate range. With consideration of the result of actual evapotranspiration, WaPOR is a useful open-access portal to obtain significant estimated results of evapotranspiration where the area is found under observation data-limited conditions. The estimated water productivity and yield of wheat align with literature provided by various researchers; demonstrating that an open-source portal is a powerful tool for evaluating and monitoring various agricultural water systems. The water delivery performance indicators of the irrigation scheme were poor equity in the 2018 irrigation season and fair for irrigation seasons from 2019 to 2022. The uniform water distribution in the irrigation scheme is classified as heterogeneous based on the dekadal and monthly time scale, the trend of even distribution of the water reduced as the crop growth stage increased. The adequacy and the relative water deficit in the irrigation scheme were classified as poor for all five irrigation growing seasons. This demonstrates that the amount of applied water in the plan is insufficient, which causes water stress and lower production. On the other hand, the irrigation system's beneficial percentage was discovered to be within acceptable limits, implying that the crop has used the applied water efficiently.

As a result of the water delivery performance assessment in the irrigation scheme, the estimated performance indicators allow us to understand the features of the irrigators and the overall trends in the irrigation system. The spatial and temporal variations of the delivery irrigation performance indicators were detected due to agronomic practice, poor water management, and operation in the irrigation scheme. By analyzing the outcomes, it is possible to gain insight into how to enhance the spatial and temporal uniformity of irrigation water distribution and the sufficiency of applied water supply to cultivated crops. This information is valuable for predicting water consumption and evaluating water delivery irrigation performance metrics related to irrigation schemes. We conclude that the open-source data provides representative information and would be used as an alternative source of data for the data-scarce regions.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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