25th International Congress on Modelling and Simulation, Darwin, NT, Australia, 9 to 14 July 2023
mssanz.org.au/modsim2023

High spatiotemporal resolution remotely sensed timeseries actual evapotranspiration estimates for irrigation management in salinity-affected areas of the southern Indus Basin

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Abstract: The Indus Basin Irrigation System (IBIS) in Pakistan is the largest contiguous irrigated system (~160,000 km^2) in the world. IBIS's crops sustain Pakistan's ~230 million people and provide a livelihood for ~90,000 farmers. Like many other irrigation systems around the world, IBIS is facing critical water management challenges, *inter alia*: (i) over-utilised surface and groundwater resources, (ii) areas with unsustainable groundwater use, (iii) areas with salinity and waterlogging reducing productivity, (iv) sediment loads reducing the capacity of reservoirs used to regulate flows and (v) climate change modifying rainfall patterns, river flow regime and evaporative demand. The system relies on two large reservoirs (16.5 km^3 combined storage capacity), 16 barrages and a vast interconnected network of channels to equitably provide water to 45 canal commands on a 10-day period. Timely and accurate estimates of water use are essential for adequate management of irrigation systems. In large and complex systems like the IBIS, distributed surface water canal or groundwater pumping volume data are often not available for water balance assessments and to monitor irrigation management practices. Remote sensing imagery and geostatistical techniques that increase data availability provide an unparalleled opportunity to estimate actual evapotranspiration (ET_a) – a proxy for water use – from large areas at the required spatial scales and temporal frequencies to assess irrigation patterns beyond the canal command scale. This paper describes the development of the first 30 m resolution and 10-day gap-free remote sensing-based ET_a timeseries from 2010–20 for salinity-affected canal commands in the IBIS facing different irrigation management challenges: (i) Sidhnai and Lower Mailsi and Lower Pakpattan canal commands with deep and rapidly declining groundwater tables in the south of Punjab province (roughly (from north to south) in the middle section of the IBIS), and (ii) the Pinyari canal command with shallow groundwater table and waterlogged areas, located in the south of Sindh province at the IBIS's tailend. The ET_a estimates were computed by scaling potential Priestley-Taylor evapotranspiration (E_0) using the vegetation index (VI)-derived scaling coefficient obtained from the CMRSET (CSIRO MODIS ReScaled EvapoTranspiration) Landsat V2.2 model at the Landsat native spatial resolution of 30 m. The 10-day frequency was achieved by taking advantage of the daily frequency VIs from the daily Moderate Resolution Imaging Spectroradiometer (MODIS), which were subsequently blended with Landsat VIs using a method capable of detecting gradual (i.e., phenological) or abrupt (e.g., floods) land cover changes. The resulting CMRSET ET_a compared reasonably well against monthly estimates from previously published ET_a products in selected canal commands, SEBAL and ET_{Look}, with monthly correlations >0.7 and percentage biases <20%. The ET_a timeseries aggregated at the canal command scale, alongside observations of canal command withdrawals, showcased the changing dynamics of irrigation water use for the two main irrigation seasons: wet summer 'Kharif' (April to September) and dry winter 'Rabi' (October to March). The analysis revealed that in south Punjab canal commands, ET_a is generally higher than canal withdrawals, potentially resulting in increased groundwater use for agriculture and aquaculture (fish farms) and a concurrent increased risk of secondary salinity. The gap between ET_a and canal withdrawals widened during Rabi. For the south Sindh canal command, the analysis showed intermittent increases in Kharif canal withdrawals surpassing ET_a, which can further aggravate waterlogging and salinisation, while there was also a widening gap between ET_a and canal withdrawals during Rabi.

The ET_a's high resolution and CMRSET's ability to dynamically detect surface water revealed recent land use change from cropping to aquaculture in south Punjab and south Sindh canal commands, which were anecdotally reported in the media but are still unquantified in terms of changes in water use and their impacts on groundwater dynamics. Other uses of 10-day VI gap-free timeseries provide the opportunity to map crops (and their water use) from season to season and assess cropping dynamics causing changes in ET_a and water use.

Keywords: *Landsat, MODIS, CMRSET, Pakistan*

1. INTRODUCTION

Increased water demand for food and fiber has led to the overexploitation of surface water and groundwater in several semi-arid irrigated systems worldwide. The development of the Indus Basin Irrigation System (IBIS) in Pakistan, the largest contiguous irrigated system in the world (~160,000 km^2), rendered increased food security for ~230 million people and a livelihood for ~90,000 farmers (FAO, 2012). As the mean annual rainfall in the IBIS is about 250 mm/year, of which 75% occurs July–August, the system is highly dependent on surface water diversions from the Indus River system. Surface supplies contribute to ~60% of the total water used for irrigation in the IBIS and the remaining is sourced from groundwater to meet evapotranspiration demand, predominantly in the fresh groundwater quality regions of Punjab and small isolated pockets of Sindh province (Ahmad et al., 2021a). This has caused the imbalance between agricultural water demands and surface (canal supplies) and groundwater use across the IBIS. This has resulted in unsustainable water use (particularly groundwater) and secondary salinisation in parts of the system (Ahmad et al., 2021b). Additionally, increased reservoir sedimentation (which reduces the capacity of the system to regulate flows) and climate change will bring further supply challenges (Ahmad et al., 2021a; Kirby and Ahmad, 2022). The IBIS relies on two large reservoirs (total storage capacity of 16.5 km^3), 16 barrages and a vast interconnected network of channels (~60,000 km of main canals) to provide water to 45 canal commands on a 10-day period (Figure 1). The 10-day period facilitates adjustments on the regulating pattern to balance shortages and surpluses and to constrain the amount of water that can be extracted (Ahmad et al., 2022). While equitable and timely distribution of canal water is the management focus, canal water or groundwater pumping volume data to assess this are often not available within main canal commands. This is essential for water balance assessments and to monitor irrigation management practices beyond the canal command scale. Remote sensing imagery to estimate actual evapotranspiration (ET$_a$) – a proxy for water use – has been used to assess the IBIS's irrigation efficiency (e.g. Peña Arancibia and Ahmad, 2020; Simons et al., 2020) at the canal command scale. The increased use of geostatistical techniques that combine 'low spatial resolution-high temporal frequency' imagery with 'high spatial resolution-low temporal frequency' imagery (e.g. Li et al., 2020) facilitates the assessment of irrigation patterns in large areas (>100 km^2) and at the required spatial scales (necessary when irrigation occurs in small <1 ha plots) and temporal frequencies (e.g. 10-day in the case of the IBIS).

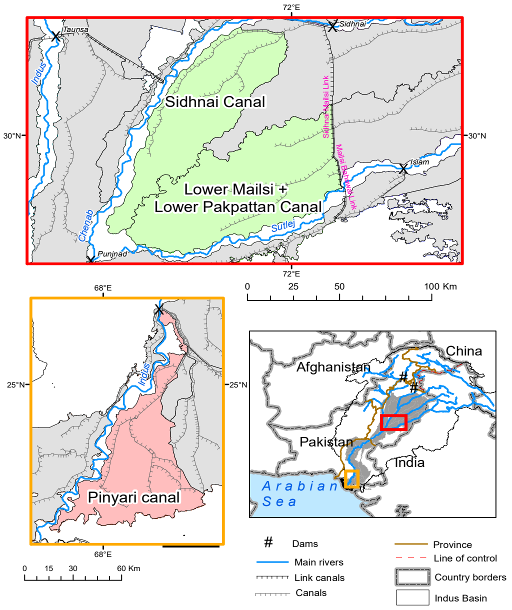

Figure 1. Geographic location of canal commands in south Punjab (green) and south Sindh (pink). Rectangle colors (red, orange) indicate their location within the Indus Basin Irrigation System (IBIS)

In this study, estimates of ET$_a$ at 30 m resolution and 10-day frequency over 2010–20 were produced to assess irrigation dynamics for salinity-affected canal commands in the IBIS. Canal commands Sidhnai and Lower Mailsi and Lower Pakpattan are in the south of the Punjab province (see Figure 1) roughly in the middle (from north to south) of the IBIS system. These canal commands have deep and rapidly declining groundwater tables. The Pinyari Canal command located in the south of Sindh province at the tail-end of the IBIS (see Figure 1) has shallow groundwater tables and waterlogged areas. For this purpose, the following steps are followed: (i) the SFSDAF algorithm (Li et al., 2020) is used to achieve continuous 10-day frequencies (i.e. at the 10th, 20th and last day of the month) and gap-free imagery by blending daily Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation indices (VIs) with 16-day Landsat (or 8-day when there are two satellites available) VIs, (ii) the VIs are used to estimate the CMRSET (CSIRO MODIS ReScaled EvapoTranspiration) scaling coefficient which is subsequently multiplied by Priestley-Taylor potential evapotranspiration (E$_0$) to obtain 10-day ET$_a$, (iii) the resulting ET$_a$ estimates are compared with two previously published locally adjusted satellite-driven ET$_a$ estimates and (iv) the seasonal (i.e. for the wet summer 'Kharif' from April to September and the dry winter 'Rabi' from October to March) canal command ET$_a$ timeseries are compared to canal water withdrawals (C$_w$) to assess interseasonal irrigation dynamics.

2. MATERIALS AND METHODS

2.1. Remote sensing vegetation indices

To produce ET_a estimates, two remotely-sensed VIs are used: (i) the Enhanced Vegetation Index (EVI) (Huete et al., 2002) and (ii) the Global Vegetation Moisture Index (GVMI) (Ceccato et al., 2002). Pre-processed MODIS EVI and GVMI 500 m 10-day cloud-masked composites were downloaded from Google Earth Engine (GEE) from the MCD43A4 V6.1 Nadir Bidirectional Reflectance Distribution Function Adjusted Reflectance (NBAR) product. Similarly, all pre-processed Landsat EVI and GVMI 30 m cloud-masked imagery were downloaded from the Landsat-5 TM, Landsat-7 ETM+ and Landsat-8 OLI sensors to produce a 10-day composite. The Landsat 8 OLI reflectance bands were then harmonised to Landsat 7 and Landsat 5 using empirical equations from Roy et al. (2016). All data downloaded corresponded to 2010−20, except for the comparison of CMRSET V2.2 against other ET_a, which covered an earlier period (see Section 2.4).

2.2. Blending of MODIS with Landsat vegetation indices

Blending of 'low spatial resolution-high temporal frequency' imagery (coarse resolution, CR) with 'high spatial resolution-low temporal frequency' imagery (fine resolution, FR) has become a widely-used method to generate 'high spatial resolution-high temporal frequency' imagery without gaps. In this study, the 10-day period in which water supply is assessed for the entire IBIS is a requirement for a water use proxy, in this case remotely sensed ET_a. Several methods exist to achieve this with varying degrees of accuracy. The Sub-pixel class fraction change information Flexible Spatiotemporal DAta Fusion (SFSDAF) method (Li et al., 2020) was used in this study due to its practicality (only requires one pair of CR-FR images before prediction and one CR image at prediction to produce a FR image at prediction) and ability of detecting gradual (i.e. phenological) or abrupt (e.g. floods) land cover changes. Due to the high cloud cover during the wet Kharif season (particularly in south Sindh), even the daily MODIS VI imagery required an additional 3D gap-filling step using the method of Wang et al. (2012) to produce a 10-day gap-free composite. A similar procedure was followed to gap-fill Landsat 10-day composites that had a few gaps. The selection of gap-free CR-FR image pairs to predict a FR image required that these be within the Kharif or Rabi seasons, given their different cropping patterns. When predicting a FR, the final image retained the observed pixels and only the gaps were replaced with predicted pixels. The correlation coefficient (r^2) and root-mean-squared error (RMSE) of the predicted FR pixels versus the observed FR pixels were used as goodness-of-fit metrics.

2.3. Meteorological data

Meteorological data, including minimum temperature, maximum temperature, downward shortwave and longwave radiation were obtained from the Multi-Source Weather (MSWX) 0.1° daily product (Beck et al., 2022) to calculate Priestley-Taylor potential evapotranspiration (E_0) for 2010−20. In addition, daily precipitation was obtained from the gauge corrected Multi-Source Weighted-Ensemble Precipitation (MSWEP) V2.2 product (Beck et al., 2019). Both products agreed well when compared against local gridded ~2.5 km monthly Hargreaves E_0 and monthly rainfall from 5 stations located within or near the canal commands used in the study. MSWEP was also satisfactorily evaluated in the southern Indus basin, against station data and other satellite products (Ahmad, 2018). The data were aggregated to 10-day frequencies for further use.

2.4. CMRSET and locally calibrated actual evapotranspiration remote sensing products

EVI and GVMI were used to obtain a scaling coefficient as described in Guerschman et al. (2022) which multiplies Priestley-Taylor E_0 to obtain 10-day ET_a for 2010−20. Also, the CMRSET algorithm incorporates a term to estimate a proxy of canopy interception that requires rainfall data (see Section 2.3). For a detailed description of the CMRSET algorithm, see Guerschman et al. (2022).

As there are no local ET_a flux tower measurements available, two independently calibrated 1 km MODIS-driven monthly ET_a datasets previously implemented in the IBIS (or part thereof) were used to evaluate the implementation of Landsat CMRSET Landsat V2.2 in the south Punjab and south Sindh canal commands: ET_{Look} (Bastiaanssen et al., 2012) and SEBAL (Ahmad et al., 2008). ET_{Look} ET_a was implemented at 1 km resolution and daily for the calendar year 2007 over the entire IBIS. SEBAL ET_a was implemented at 1 km resolution and monthly for the year 2004–05 (October to September) in the Punjab province. CMRSET Landsat V2.2 data were subsampled (using averaging) to 1 km spatial resolution and monthly frequency for comparison with ET_{Look} and SEBAL. The correlation coefficient (r^2) and percentage bias (PB) were used as goodness-of-fit-metrics in the comparison.

2.5. Canal water withdrawals

Main canal deliveries at 10-day timestep for 2010−2020 were obtained from the provincial irrigation departments of Punjab and Sindh, and Indus River System Authority (ISA).

3. RESULTS AND DISCUSSION

3.1. Blending of MODIS with Landsat vegetation indices

Figure 2 shows an example of the blending results in south Punjab (Sidhnai Canal) for the 10-day period composite corresponding to 1 to 9 September 2012. The original Landsat composite (first column) in timestep 2 (T2) only had Landsat 7 imagery available, and gaps due to the scan-line error, masked clouds and satellite footprint can be seen. The MODIS/Landsat blended image (second column) showcases the results of the SFSDAF algorithm. The MODIS composite at T2 (third column) is shown for reference. This blended composite has a mean observed EVI of 0.43, r^2 of 0.77 and RMSE of 0.09, whereas for GVMI the mean is 0.27, r^2 of 0.53 and RMSE of 0.09. Note that GVMI values are generally lower than EVI (except in water) and many are close to zero in arid conditions present in the IBIS non-irrigated areas, and hence the r^2 tends to be lower. The mean statistics for ~52 billion pixels are:

- for a mean EVI=0.19, the mean r^2=0.67 (±0.18 stdev) and RMSE=0.05 (±0.02 stdev)
- for a mean GVMI=0.18, the mean r^2=0.58 (±0.20 stdev) and RMSE=0.07 (±0.03 stdev).

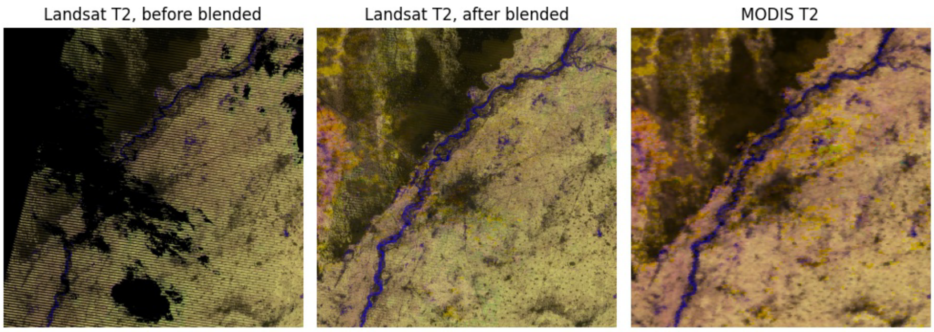

Figure 2. Example of a Landsat 10-day composite corresponding to 1 to 9 September 2012 in timestep 2 (T2), the first column shows the image with gaps, the second column the SFSDAF blended image composite and the third shows the 10-day MODIS composite for reference

3.2. CMRSET and comparison with locally calibrated actual evapotranspiration remote sensing products

Figure 3 shows the comparison of CMRSET V2.2 ET_a against two independent ET_a products – ET_{Look} (during the 2007 calendar year) and SEBAL (from October 2004 to September 2005). Note that SEBAL only covers the Punjab.

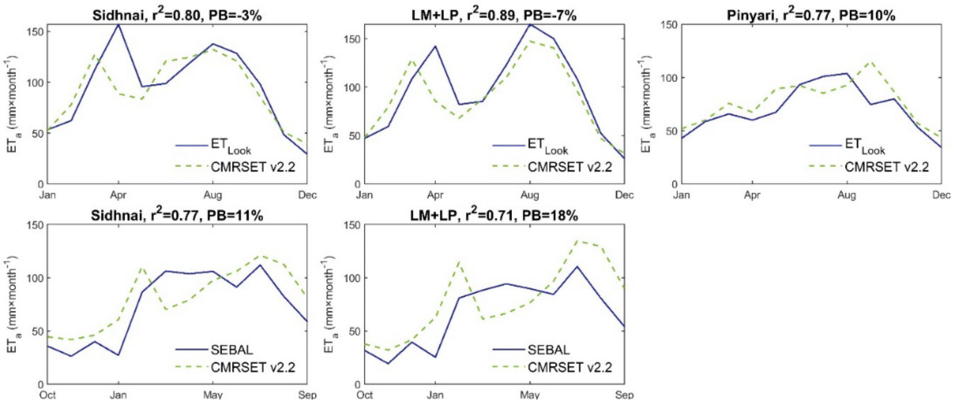

Figure 3. Comparison of CMRSET V2.2 ET_a (green dashed line) against ET_{Look} during 2007 calendar year and SEBAL from October 2004 to September 2005 (both in blue solid lines). The top row shows the comparison against ET_{Look}, and the bottom row shows the comparison against SEBAL (only south Punjab canal commands). LM+LP = Lower Mailsi and Lower Pakpattan; PB = percentage bias

CMRSET ET_a compares well both in terms of magnitude and seasonality, although in Punjab's CMRSET's peak in Rabi (October to March) happens in March and in April for ET_{Look}. Crop calendars state that the most widespread Rabi crop in the region, wheat, is harvested in April, however, ET_a reaches its peak in March (Soomro et al., 2018). Similar seasonality of double cropping systems is not observed in SEBAL. Overall, monthly r^2 were >0.7 and percentage biases <20%.

Figure 4 shows the mean 2010−20 seasonal spatial ET_a for canal commands in Punjab (top row) and Sindh (bottom row) as well as the respective trends. In Punjab, the spatial mean ET_a for Kharif is 592 mm/season ±108 stdev (max=1340 mm/season, min=97 mm/season) whereas in Rabi, it is 370 mm/season ±64 stdev (max=717 mm/season, min=42 mm/season). Spatial patterns of highest ET_a are prevalent in open water areas whereas low ET_a patterns in agricultural regions are largely confined to high salinity areas (as shown in Ahmad et al., 2019). There are generally no large positive/negative trends (±50 mm/season per season) in Punjab in either season, except for areas to the north in the Sidhnai Canal (see Figure 4, red rectangle). In these areas, growth in high ET_a values (>500 mm/season) occurs in both seasons, which denotes the presence of surface water.

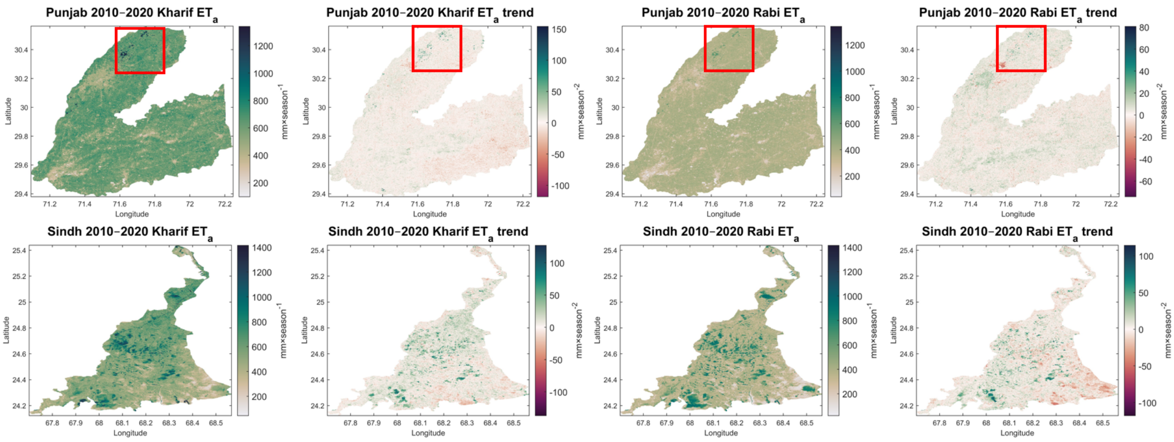

Figure 4. CMRSET V2.2 mean seasonal (Kharif and Rabi) ET_a (mm/season) and associated trends for the two south Punjab canal commands (top row) and the Sindh canal command (bottom row). The red rectangle shows the areas with the highest increasing trend in ET_a in Punjab

In Sindh, the mean ET_a for Kharif is 544 mm/season ±168 stdev (max=1414 mm/season, min=44 mm/season). For Rabi, the mean ET_a is 404 mm/season ±171 stdev (max=969 mm/season, min=27 mm/season). In contrast, there are large positive/ trends (>50 mm/season per season) in Sindh in both Kharif and Rabi and ET_a values in those areas with high trends are high (500 mm/season). There is evidence of a drive to introduce freshwater aquaculture in these areas as farmers are moving from cropping to aquaculture, as indicated by the increase in production from 2012 to 2016 (Das, 2018).

3.3. Interseasonal irrigation dynamics

Interseasonal mean canal command ET_a timeseries were compared to C_w (Figure 5). During Kharif in south Punjab canal commands (Sidhnai, Lower Mailsi and Lower Pakpattan), both ET_a and C_w remain largely steady throughout the study period (2010−20), with ET_a being larger than C_w. Although the aggregated ET_a considers the entire landscape (considered conservative as non-cropped areas are included) there is a deficit between ET_a and C_w. As annual rainfall in this region is less than 200 mm/year, the deficit between ET_a and C_w is generally compensated by groundwater withdrawals and both canals have significant ($p < 0.01$) groundwater declines (Ahmad et al., 2021b). The deficit during Rabi widens over the years.

Conversely, the Pinyari Canal in south Sindh receives an excess of intermittent C_w during Kharif, which could aggravate salinisation and waterlogging. As in Punjab, Rabi C_w are decreasing over the years and the deficit widens. Ahmad (2018) and Ahmad et al. (2021b) attribute this to a reduction in available surface water storage due to dam sedimentation, climate change/variability and a concurrent reduction in basin inflows from gradual upstream development outside of Pakistan.

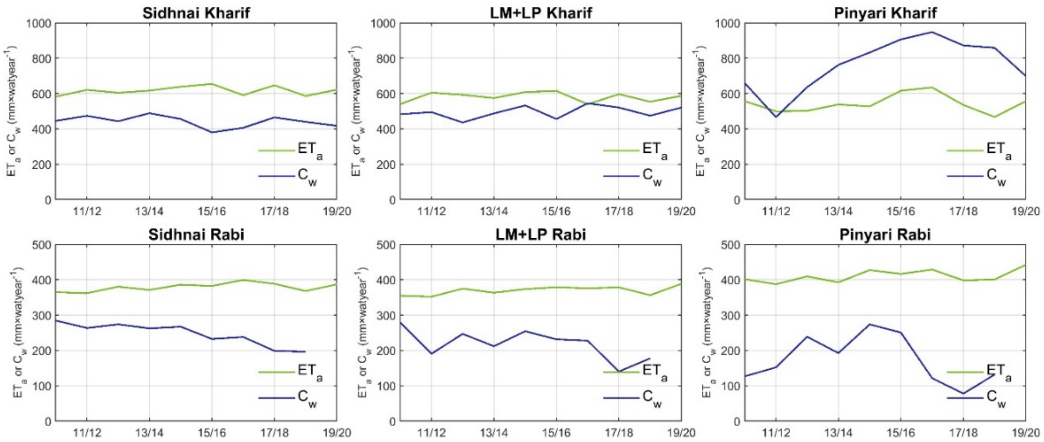

Figure 5. CMRSET V2.2 interseasonal (Kharif and Rabi) ET_a (green line) and canal water withdrawals (C_w) (blue line) in the two south Punjab canal command areas (columns 1 and 2) and the south Sindh canal command area (column 3). The top row shows the Kharif season, the bottom row shows the Rabi season

4. CONCLUSION

This study showcased the development and evaluation of the first 30 m spatial and 10-day temporal resolution remote sensing based actual evapotranspiration (ET_a) assessment from 2010-20 for the selected salinity-affected canal commands in the Indus Basin Irrigation System (IBIS). The 10-day frequency is required to match the 10-day period in which adjustments are made to regulate flows to balance shortages and in the IBIS's canal commands. The spatial resolution and temporal frequency can be readily used to assess intracanal command dynamics, thereby facilitating the explicit assessment of irrigation performance (e.g., equity, variability, reliability), net groundwater use and water balances. Further uses of the ET_a data and the vegetation indices (VIs) used in its implementation include crop mapping and assessments of land use change. This was explored in this study as there is evidence of increased freshwater aquaculture in both south Punjab and south Sindh canals. Understanding changes in ET_a and associated changes in water balances, and identifying a shift to other crops or land use (such as aquaculture), is critically important for devising appropriate policies and strategies for sustainable water management in the IBIS.

ACKNOWLEDGEMENTS

This work is based on research funded by the Australian Centre for International Agricultural Research (ACIAR) Adapting to Salinity in the Southern Indus Basin (ASSIB) project (LWR/2017/027), with additional funds provided by CSIRO Environment.

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