KEY POINTS

- A remote sensing-based decision support system (DSS) was developed for an irrigation system covering 756,000 hectares in Punjab, Pakistan.
- The DSS provides insight into irrigation requirements based on actual evapotranspiration and soil moisture contents. Results showed that delivered canal water varied among divisions, secondary canals called distributaries, and crop seasons, implying the system's potential for water distribution improvements.
- Soil moisture estimates confirmed that deficit irrigation was generally practiced for the study year 2017–2018, but areas with conjunctive use are wetter.
- The inequity in delivery may be minimized by reallocating water between divisions. Inequity within a division can be minimized by modifying the rotation plan of the division.
- Key limitations of the study could be addressed with ground validation and analyzing more than 1 year of historical satellite data. In Punjab, irrigation managers recognize this methodology as a potential tool for improving equity and productivity at the distributary level. A follow-up would be to operationalize the remote sensing-based DSS by extending the model to provide forecasts.

Optimization of Canal Management Based on Irrigation Performance Analysis Using Satellite Measurements

INTRODUCTION

Even in supply-based irrigation systems, canal management could be optimized using satellite imagery, as demonstrated in the Lower Bari Doab Canal (LBDC) pilot demonstration activity (PDA) reported here.¹ Free availability of satellite images, high-speed computing, and surface energy balance models have determined a suite of irrigation performance indicators (IPIs) a realistic possibility. These indicators reveal various aspects of crops, water supply, and irrigation water use. The availability of such information can guide irrigation managers to alter canal management practices and maximize the equity in water delivery.

The Asian Development Bank (ADB) supported a PDA to use remote sensing-derived information to complement classic canal flow data with spatially discrete field-level water use information for improving equity in canal water delivery. The study was carried out in the LBDC, Punjab, Pakistan, which was rehabilitated with ADB support.² The study used historical canal discharge and satellite data collected in 2017 and 2018³ for Rabi (spring) and Kharif (autumn) seasons.⁴ The LBDC command area is approximately 756,000 hectares and consists of a main (primary) canal receiving water from Balloki Barrage and 70 distributaries (secondary canals). Administratively, the LBDC is divided into four divisions—Balloki, Okara, Sahiwal, and Khanewal—each with an independent water rotation schedule for its respective distributaries (Figure 1).

¹ This study was financed by the Water Financing Partnership Facility regional technical assistance on Knowledge and Innovation Support for ADB's Water Financing Program (TA 6498-REG). The title of the study is *SEBAL Analysis of Irrigation Performance to test a Near Real-Time DSS methodology for Irrigation Canal Management—A Pilot Demonstration Activity in Lower Bari Doab Canal, Pakistan*.

² This brief was jointly prepared by Asad Zafar, senior project officer (Water Resources), Central and West Asia Department (CWRD), ADB; Sanmugam A. Prathapar, ADB consultant; Wim Bastiaanssen, ADB consultant and chief executive officer of IrriWatch; and Wakas Karim Awan, senior geographic information system specialist, Punjab Irrigation Department. From ADB's Sustainable Development and Climate Change Department, Jelle Beekma, senior water resources specialist; Xueliang Cai, water resources specialist; and Paolo Manunta, senior infrastructure specialist (Earth Observation), reviewed an earlier draft of the brief and provided valuable comments. Umair Amin, project analyst, CWRD, ADB, provided administrative support to the study.

³ ADB. 2006. *Report and Recommendation of the President to the Board of Directors: Proposed Multitranchise Financing Facility to the Islamic Republic of Pakistan for the Punjab Irrigated Agriculture Investment Program*. Manila.

⁴ Pakistan has two principal crop seasons: (i) Kharif (autumn), with planting in April and harvesting in October–December; and (ii) Rabi (spring), with planting in October–December and harvesting in April–May.

Figure 1: Lower Bari Doab Canal Command

Source: Asian Development Bank.

A key performance indicator used by the Punjab Irrigation Department (PID) is the delivery performance ratio, the measured discharge ratio to the design discharge. Variation in canal water delivered per unit irrigable area per unit time is a direct measure of inequity. The PID monitors water delivered to distributaries and records flows in their real-time flow monitoring system (RTFMS). The data in the RTFMS do not inform how crops consumed the canal water or whether it is sufficient to meet crop demand. This useful and necessary addition can be provided by remotely sensed satellite data combined with energy balance models.

In this study, freely available Landsat and Sentinel satellite images are used to measure various types of irrigation-related information like irrigated land, main cropping patterns, actual and potential evapotranspiration, soil moisture in the root zone, and dry matter crop production. A detail of 30 meters x 30 meters has been used, and performance indicators were produced for every 8 days of

the water rotation cycle. The inclusion of remote sensing makes it feasible to shift decision-making from water supply based on various crop and water-related assumptions to a demand-based system that includes cropped area, irrigation water requirements, water deficit (demand-supply), and crop production. Information on evapotranspiration and soil moisture can be utilized to start tracking what happens with the canal water after leaving the distributary canal. It will also inform how canal water is supplemented by rain and groundwater to meet evapotranspiration requirements.

For a proper understanding, it is essential to introduce the following key processes. Crop water requirements result from farming practices, type of crop, crop variety, planting density, and cropping calendar, among others. It is also termed as the potential evapotranspiration of a cropping system. The irrigation water requirement corrects the crop water requirements for effective rainfall and the water losses between the offtake and the crop's

root zone. Consumptive use is the true evaporative water use; this water is no longer physically present in the river basin and cannot be recaptured. On the contrary, nonconsumed water drains to surface watercourses or recharges the aquifer (Simons et al., 2020).

The Surface Energy Balance Algorithm for Land (SEBAL) model has been used as the core engine to process the mentioned key biophysical parameters. The advantage of an energy balance is the direct provision of actual consumptive use without prior information on water distribution and abstractions (Bastiaanssen, Ahmad, and Chemin 2002). Soil moisture is determined by the method proposed by (Scott, Bastiaanssen, and Ahmad 2003).

PROBLEM STATEMENT

In Pakistan, irrigation departments aim to provide an adequate amount of water to meet demand (evapotranspiration_{pot}) in a reliable and socially equitable manner. Water for the crops may be sourced from a combination of canal water, groundwater, and rain. However, irrigation system managers have control only over the volumes and timing of canal water supplies. With the changes

in cropping patterns and conjunctive use practices, they have incomplete information to prepare reliable plans. Quasi-real time satellite measurements can solve this problem. This study explores if canal discharge data supplemented with remote sensing data can make canal water distribution more socially equitable.

METHODOLOGY

The evaluation of irrigation performance using key indicators based on remote sensing measurements is a framework that has existed for more than 30 years in the international scientific community. Murray-Rust and Snellen (1993); Bastiaanssen and Bos (1999); Bastiaanssen, Molden, and Makin (2000); and Bos, Burton, and Molden (2005) published a framework that includes aspects of equity, adequacy, reliability, flexibility, and productivity. In this study, a standard list of 15 IPIs (Table 1) was identified. However, the analysis focused on indicators that require the least adjustments and interpretations. The level of maturity is added to highlight the large difference in development history, where more stars imply a higher level of acceptance in the scientific community. Only five IPIs were used for canal water optimization and are highlighted in gray shade.

Table 1: List of 15 Irrigation Performance Indicators

No.	Indicator	Maturity	Description
IPI ₁	Q_{cw}/A_{irr}	*****	Canal water supply per unit area (irrigable land)
IPI ₂	$IWR = (ET_{pot} - P_{net})/Eff$	*****	Irrigation water requirements per unit area (irrigable land)
IPI ₃	Q_{cw}/IWR	****	Adequacy canal water supply
IPI ₄	ET	*****	Total consumptive use per unit of irrigated land (A_{irr})
IPI ₅	ET _{crop}	****	Total consumptive use per unit of irrigated crop
IPI ₆	ET _{cw}	**	Consumptive use originating from canal water per unit of irrigated land
IPI ₇	ET _{cw-crop}	*	Consumptive use originating from canal water per unit of irrigated crop
IPI ₈	$\emptyset/A_{irr}$	****	Soil moisture root zone per unit of irrigated land
IPI ₉	$\emptyset/\emptyset_{crit}$	***	Under-irrigation per unit of irrigated land
IPI ₁₀	$\emptyset/\emptyset_{FC}$	***	Over-irrigation per unit of irrigated land
IPI ₁₁	ET _{pot} - ET _{act}	****	Crop water deficit of irrigated land
IPI ₁₂	$1 - (ET_{act}/ET_{pot})$	****	Relative water deficit of irrigated land
IPI ₁₃	CV($\emptyset(t)$)	***	Reliability of irrigation (once per season)
IPI ₁₄	(Bio/ET)	*****	Water productivity per unit of irrigated land
IPI ₁₅	(Bio/ET) _{crop}	*****	Water productivity per unit of irrigated crop

$\emptyset$ = soil moisture, A_{irr} = area of irrigable land, A_{irr} = area of irrigated land, act = actual, Bio = biomass, crit = critical, CV = coefficient of variation, cw = canal water, Eff = efficiency, ET = evapotranspiration (consumptive water use), ET_{act} = actual evapotranspiration, ET_{act-crop} = actual evapotranspiration from specific crop, ET_{act-cw} = actual evapotranspiration occurred from canal water, ET_{act-cw-crop} = actual evapotranspiration from specific crop contributed by canal water, ET_{crop} = evapotranspiration from specific crop, ET_{cw} = same as ET_{act-cw}, ET_{pot} = potential evapotranspiration, ET_{cw-crop} = evapotranspiration occurred by canal water from specific crop, FC = field capacity, IPI = irrigation performance indicator, IWR = irrigation water requirement, P_{net} = effective rainfall, pot = potential, Q_{cw} = canal water supply, t = transpiration.

Note: More stars (*) imply a higher level of maturity or acceptance of the IPI in the scientific community. The five IPIs, which are shaded in gray, were the indicators used for canal water optimization.

Source: ADB's Technical Assistance Study Report.

Discharge data through the head regulator is integrated with satellite measurements to approximate IPI_1 , IPI_3 , IPI_6 , and IPI_7 . The availability of canal flow thus remains necessary for computing all indicators. Traditional performance assessment relies on discharge measurements; however, in the absence of discharge data, 11 IPIs can still be derived—these are sufficient to assess adequacy, equity, reliability, and productivity. This is an important fact and concept for the evaluation of irrigation schemes in Asia that have limited access to discharge measurement. Rabi and Kharif occupy both approximately 180 days (i.e., eight rotation cycles), and the 15 IPIs posed were computed for every irrigation cycle and every distributary. Unitless IPI values are benchmarked against their target values. The $IPI_{actual}/IPI_{target}$ ratio is informative and indicates which aspect of irrigation operations goes according to expectations and which aspects require more attention.

MAIN FINDINGS

Gini coefficients of water delivered in 2017 and 2018 showed that water delivery to gross command of distributaries in Kharif

was more equitable than water delivered in Rabi. A possible reason is that the flow in the Rabi is well below the design. Modification to the rotational plan to maintain the water surface level as close as possible to the design may improve equity. Better estimates of indents and revision of rotation plans based on historical performance may improve canal water supply equity across the distributaries. Canal water per unit of irrigated land for Rabi and Kharif season in LBDC is shown below in Figures 2 and 3. Seasonal accumulated crop evapotranspiration for distributaries varies (Figures 4 and 5). Sahiwal appears to have a higher evapotranspiration during both seasons than other divisions, which can be attributed to more orchards and commercial crops in the area.

The water deficit assessment of the study for the four divisions is presented in Table 2 (p. 6). It implies that Khanewal and Sahiwal are having higher consumptive water use and less water stress than Balloki and Okara, possibly because of the groundwater's intensive use. When discussing consumptive use, crop water deficit (IPI_{11}) is also therefore an important indicator.

Figure 2: Canal Water per Unit Irrigable Land (Rabi)

CW = canal water, d = day, IPI = irrigation performance indicator, mm = millimeter.

Note: Pakistan has two principal crop seasons: (i) Kharif (autumn), with planting in April and harvesting in October–December; and (ii) Rabi (spring), with planting in October–December and harvesting in April–May.

Source: ADB's Technical Assistance Study Report.

Figure 3: Canal Water per Unit Irrigable Land (Kharif)

CW = canal water, d = day, IPI = irrigation performance indicator, mm = millimeter.

Note: Pakistan has two principal crop seasons: (i) Kharif (autumn), with planting in April and harvesting in October–December; and (ii) Rabi (spring), with planting in October–December and harvesting in April–May.

Source: ADB's Technical Assistance Study Report.

Figure 4: Consumptive Water Use (Rabi)

ET = consumptive water use, d = day, IPI = irrigation performance indicator, mm = millimeter.

Note: Pakistan has two principal crop seasons: (i) Kharif (autumn), with planting in April and harvesting in October–December; and (ii) Rabi (spring), with planting in October–December and harvesting in April–May.

Source: ADB's Technical Assistance Study Report.

Figure 5: Consumptive Water Use (Kharif)

ET = consumptive water use, d = day, IPI = irrigation performance indicator, mm = millimeter.

Note: Pakistan has two principal crop seasons: (i) Kharif (autumn), with planting in April and harvesting in October–December; and (ii) Rabi (spring), with planting in October–December and harvesting in April–May.

Source: ADB's Technical Assistance Study Report.

Table 2: Water Deficit Assessment in the Lower Bari Doab Canal's Divisions

Key Indicator	Bhalloki		Okara		Sahiwal		Khanewal	
	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif
Crop Water Requirement	3.4	4.3	3.3	5.1	4.2	5.8	3.4	5.5
Canal Water Supply Per Unit Area (IPI ₁)	1.7	3.1	1.2	2.1	1.2	2.1	1.4	2.5
Irrigation Water Requirement (IPI ₂)	4.9	5.4	5.0	6.0	6.0	8.7	5.1	8.0
Consumptive Use (IPI ₄)	1.6	1.6	1.5	1.7	2.6	5.3	1.9	4.0
Crop Water Deficit (IPI ₁₁)	1.8	2.7	1.8	3.4	1.6	0.5	1.5	1.5

IPI = irrigation performance indicator.

Note: Pakistan has two principal crop seasons: (i) Kharif (autumn), with planting in April and harvesting in October–December; and (ii) Rabi (spring), with planting in October–December and harvesting in April–May.

Source: ADB's Technical Assistance Study.

DECISION SUPPORT SYSTEM

Based on the IPIs developed, a decision support system (DSS) has been designed to help optimize canal water distribution. First, canal water is distributed equally among divisions. The average canal water supply to all four divisions is set at the average for Rabi and Kharif. Second, these values were broken down into periodic values that correspond to the time profile of irrigation requirement and consumptive use. Next, optimization of canal flow is achieved

for every distributary. The optimization is based on the principles of (i) equity between divisions, (ii) equity between distributaries, (iii) seasonal profile of irrigation water requirement and consumptive use, (iv) reduction in over-irrigation and under-irrigation, and (v) increase in crop water productivity. Hence, the DSS recomputes the total fixed volume of canal water flowing through all direct offtakes' head regulators investigated. The PID may consider to adapt canal flow for each irrigation cycle and/or to revise rotation plans for the divisions and distributaries.

CONCLUSION

The presented remote sensing-based IPI framework provides an independent check of the irrigation performance monitoring beyond water releases at the outlet level. It offers an opportunity to monitor water stress faced by crops and reflect the performance of secondary canals against division and interdivision rotation plans. There is a scope to improve irrigation management and improve inequity within the LBDC and possibly across the Indus Basin Irrigation System.

The study was carried out jointly with the PID. Training sessions were provided, and software was jointly developed. The PID experienced the data to enrich understanding of the real canal operations and has decided to continue developing the prototype DSS. Two significant modifications are suggested following the successful testing of the remote sensing approach. First is to revise division rotation plans based on the analysis of water delivered using data available in the RTFMS and water resources management information system databases. Consideration must

be given to operate the canals as close as possible to the design in both seasons during high crop demand and save during less demand. The DSS developed in this PDA can assist irrigation managers in revising rotational plans in both seasons. Second is to improve the setting of indents during the irrigation season, using satellite-derived crop water demand ($\text{evapotranspiration}_{\text{pot}}$), consumptive use (evapotranspiration), and soil moisture status. This study has explored 15 IPIs and enlists five of them as key IPIs. The new DSS provides a good option to make canal water flows more flexible.

In light of the implementation of the Water Act 2019 to perform integrated water resources management, this study gives the PID an immense opportunity for closely monitoring consumptive water use by agriculture and soil moisture in the root zone. The use of scarce water resources for improved equity and productivity can be regulated better. It might be applicable to comparable *warabandi* (water rotation) and protective irrigation systems.

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