Mapping Impact of Farmer's Organisation on the Equity of Water and Land Productivity: Evidence from Pakistan

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In 1980, the World Bank began to promote Participatory Irrigation Management (PIM) reforms to overcome inequities in the distribution of irrigation water. This paper attempt to map the land and water productivity under the PIM and Non-PIM irrigation schemes in the Indus Basin Irrigation System (IBIS). This study integrates the remotely sensed datasets along with the traditional survey approach for data collection to holistically understand the performance of different irrigation governance regimes. We found that although the reform area in Sindh is performing better on many equity-related indices, a considerable inequity still persists between the head and tail reaches of the main canal. The variation in crop choices is the main reason for disproportionate economic return per unit of land and water and the role of farmer's organisation to reduce the inequitable distribution of the water resource has limited success so far. However, it is seen that farmers' role in improved irrigation management can be enhanced with better future legislation and devolution of more power and authority rather than only responsibility. We propose that the PIM theory of change, accompanied by mobilisation activities designed to generate hydro-solidarity and support the enactment of new social roles in contexts of social power asymmetries, could improve outcomes under PIM.

Keywords: Farmers Managed Irrigation Schemes, Indus Basin, Water Productivity, Gini Coefficient, Water Distribution Inequity, Irrigation Performance Indices

1. INTRODUCTION

The term hydraulic mission is used by different scholars to refer to the late 18th and 19th century's mega irrigation infrastructure engineering project era (Brian Chatterton, 2011; Molle, Mollinga, & Wester, 2009). The mid-18th century was also a century of colonialism. Colonial powers captured markets for their consumption of surplus production and exploitation of the raw material from these markets. During this era, large dams, barrages/headworks, and canals were constructed to divert the water to high-elevation contours for irrigation purposes. Further unsustainable exploitation of natural resources

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increased during the 19th century after the Soviet Revolution in 1917. This Cold war era witnessed the building of mega infrastructure in different parts of the world like IBIS and the Ammo River basin development in the former Soviet states. During this era, water scarcity was solved through supply-side infrastructure. Irrigation bureaucracy and irrigation professionals were trained to manage this large-scale irrigation infrastructure.

Water shortages, salinity, waterlogging, and significant conveyance losses at the watercourse level are problems for Pakistan's irrigated agriculture. Pakistan diverts 75 percent of the 139 million acre-feet (171 km3) of annual water flow from the rivers of the Indus Basin to its canal irrigation system. However, conveyance losses in the canal system cause 25 percent of this surface water, or 26 million acre-feet (32 km3), to be lost (Mekonnen, Channa, & Ringler, 2015).

Irrigation plays a vital role in Pakistan's economy and prosperity, yet its irrigation infrastructure is chronically underfunded. The Irrigation system in Punjab is financially unsustainable, as it recovers only 20 percent of the O&M costs (Commission, 2012). Water pricing and recovery of the costs of irrigation investment, operation, and maintenance have been contentious issues for many decades. Current irrigation system inefficiencies in Pakistan result from poor cost recovery for irrigation and drainage and underinvestment in operation and maintenance (Tsur, Dinar, Doukkali, & Roe, 2004). Other underlying issues include inefficiencies in the public sector, the design of the irrigation system, the nature of the agricultural society and its system of land tenure, and the political economy that results from the interaction of all these elements (Mekonnen, et al. 2015).

To overcome these challenges World Bank in a policy paper of 1992, Bank describes three priority areas for future water management as main pillars: water as an economic good; improved institutional arrangement involving greater stakeholder participation, private sector, and NGOs; comprehensive management of water (Briscoe, Anguita, & Peña, 1998). International Conference on Water and Environment—held in 1992, a.k.a. Dublin Conference, concluded: "water has an economic value in all its competing uses and should be recognised as an economic good" (Lundquist, 1997). Following the Dublin principles, the United Nations Conference on Environment and Development (1992) also endorsed the idea—of water as an economic good (Gleick, Wolff, Chalecki, & Reyes, 2002).

Therefore, the participatory introduction of the institutional reform in Pakistan was interlinked with the reform's international context and streamlined with the neoliberal economic agenda of water reforms and decentralised governance. Many developing countries adopted these reforms under the Bank's guidance and funding (Liebrand, 2019; Santiso, 2001; Vermillion, 1997). Third-world countries with economic dependence on the Bank's lending face severe financial indebtedness challenges (Santiso, 2001). The state's functioning and performance in service provision and developmental activities were questioned. Under these circumstances, market forces and the private sector were portrayed as the "only" compelling alternative to government, and the state is claimed to be inefficient (Desmond McNeill, 1998). The "only" option left behind includes the water users and other private sectors in water management as an integral part of an alternative form of participatory water governance movement (M. O. Wilder, 2002). This alternative decentralised governance was believed to improve "resource allocation, efficiency, accountability, and equity". Water pricing and participatory governance were considered

as a means to achieve the goals mentioned above. After its widespread adoption, the "new" decentralised governance provides a tremendous body of literature highlighting its impacts and outcomes and discussing different strategies of decentralisation in different countries and contexts (Bandyopadhyay, Shyamsundar, & Xie, 2010; Ghumman, Ahmad, Hashmi, & Khan, 2014; Mukherji, Fuleki, Suhardiman, & Giordano, 2009; Parthasarathy, 2000; Raby, 2000; Reddy & Reddy, 2005; Senanayake, Mukherji, & Giordano, 2015; Sinclair, Kumnerdpet, & Moyer, 2013; Suhardiman, Giordano, Rap, & Wegerich, 2014; Uysal & Atiş, 2010; Douglas L Vermillion, Samad, Pusposutardjo, & Arif, 1999).

The World Bank has had a long history of lending in Pakistan's water sectors since the Indus Water Treaty (1960). Initially, this lending focused on infrastructure development, and then in the 1980s, its focus shifted from infrastructure development to transforming the institution. In 1994, the Bank studied the water sector and prepared a report entitled "Pakistan—Irrigation, and Drainage: Issues and Options". This report points out that in Pakistan, as in many other countries, the government treats irrigation water as a public good, whereas it is a private tradable good, for which markets can operate (Briscoe & Qamar, 2005).

In the early conceptualisation, these reforms faced challenges from two quarters; one is the powerful irrigation bureaucracy which considered these reforms unfeasible because farmers can't manage the technical structure and other large landowner farmer's associations labeled these reforms as an attempt to privatise the irrigation system. Through these tactics' irrigation, bureaucracy amended the initial idea and limited power distributed to farmers' organisations established in the nested irrigation governance as shown in Figure 1.

Despite the difficulties the PIM process has encountered in Pakistan, some case studies show that minors and farmer-managed distributaries are doing better than they did before the reform. Research that evaluated the effectiveness of state-managed and farmer-managed irrigation systems in Punjab, where irrigation management transfer was implemented in the pilot phase (Ghumman, et al. 2014; Latif, et al. 2014). In this study, multiple distributional equality criteria were used to compare the performance of both state-managed and farmer-managed distributaries. As an evaluation indicator, the Delivery Performance Ratio (DPR), geographical and temporal coefficients of variation, farmers' net income, and land and water productivities are utilised. Results showed that all of the aforementioned metrics were performed substantially better by the farmer's management distributary. This study also showed that despite the performance of farmers' managed irrigation systems being superior to state-controlled irrigation systems, the FMIS system's performance was also subpar.

Contrarily, a recent World Bank analysis found that farmers' organisations that administer distributaries have higher rates of water theft than bureaucratically controlled irrigation systems. The discharge data obtained in Punjab were used in this investigation. The results of this study also show that water theft was more prevalent along the channels when there was a greater land disparity and large landowners were located near the head of the channel.

This article updated the previous Pakistani analyses by using the remotely sensed data for performance comparison between PIM and Non-PIM irrigation schemes rather than solely relying on data provided by Irrigation Department and data collected through donor-funded surveys. The prime objective of this study is to assess whether reforms have any impact to improve the distributional equity of canal water economic dividend.

1.1. Irrigation Water Management and Governance in IBIS

Water shortage was addressed during the colonial era using supply-side measures such as massive dams, barrages/headworks, and canals (Yu et al., 2013). To oversee this extensive irrigation system, specialists and bureaucrats in irrigation management were educated. IBIS, one of the biggest contagious irrigation systems, is, therefore, a supply-driven irrigation system that typically diverts water from barrages or headworks to main canals, which then feed branch canals, which in turn feed tertiary level irrigation systems, known as distributary/minor irrigation systems. Further distributary and minor diverted water to an exit are applied largely using surface irrigation—flooding method. Up to the tertiary tier, the irrigation department alone is responsible for managing this irrigation structure, which is controlled by a layered framework. The community only controls watercourses below the tertiary tier. IBIS has a special warabandi system that distributes water to each field along each watercourse on a pro-rata basis; this area is also referred to as the water allotment. Water is dispersed progressively across fields based on the warabandi timetable after being drained from the outlet (known as Pacca Warabandi).

To undertake the watercourse lining initiative (directed by the agricultural department), informal community organisations were initially grouped into Water User Associations/Water Course Associations (Byrnes, 1992). These WUA/WCA supplied human work as well as a certain cash contribution (which fluctuated over time). Following that experience, the World Bank increased its pressure on the government to grant these community organisations access to tertiary and secondary levels of organisational structure.

Fig. 1. Comparison of Centralised Irrigation Department with Participatory Reform
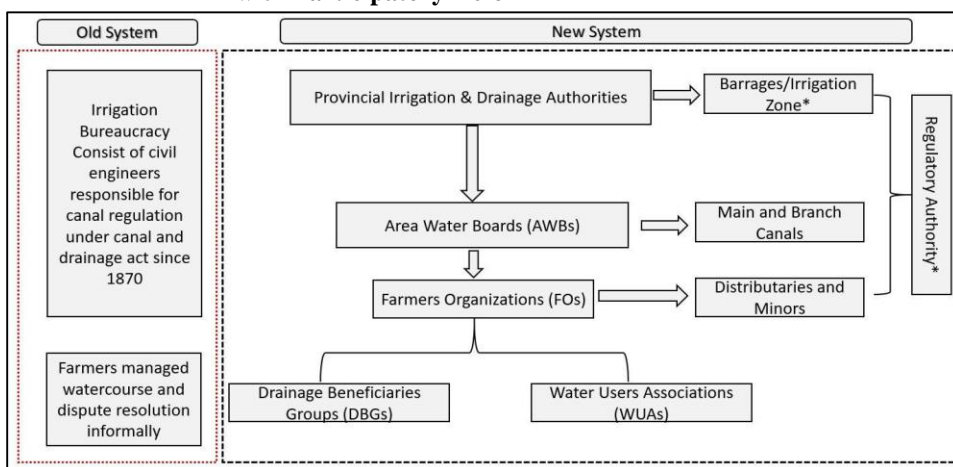
2. METHODS AND MATERIALS

## 2.1. Reform and Non-Reform Area Canals Description

For this study, the canal command regions of Punjab and Sindh were chosen. For a comparative examination of the reform, two canals from each province were looked at; one was in a region where the participatory governance system is/was applied, and the

other was in one where the provincial irrigation department alone governs. Bahawalpur and Bahawalnagar canal circles in Punjab were chosen for this purpose because of their nearly identical geophysical and climatic qualities. The princely realm of Bahawalpur included Bahawalpur and Bahawalnagar. The Sutlej Valley project was created by the Nawab of Bahawalpur with the ai of British funding on the Sutlej River. Rohri and Nara canals in Sindh were chosen because of their geophysical and climatic qualities. On the Left Bank of the Indus River are both of these canals. Due to part of its alignment with the Indus River floodplain zones, the Rohri Canal Command offers certain comparative advantages. Wheat and cotton are the main crops grown along these canals. To comprehend the irrigation system performance geographically, each main canal system was separated into three regions, namely the head, middle, and tail, as illustrated in Figure 2.

2.2. Remote Sensing-based Irrigation Performance Indicators

To evaluate the water usage performance indicators internationally, remote sensing data is frequently employed. This reliable approach helps resource managers make efficient judgments regarding the regulations and allocation of water throughout time and space. A greater knowledge of the actual functioning of various irrigation schemes and their water delivery system is possible thanks to remote sensing-based measurements of the Normalised Difference Vegetation Index (NDVI), actual evapotranspiration, and evaporative fraction. In this work, in addition to the conventional survey-based estimates, we also estimate the time series of cropping intensity, sufficiency, dependability, and economic water productivity.

Fig. 2. Study Area Selected Canals Command
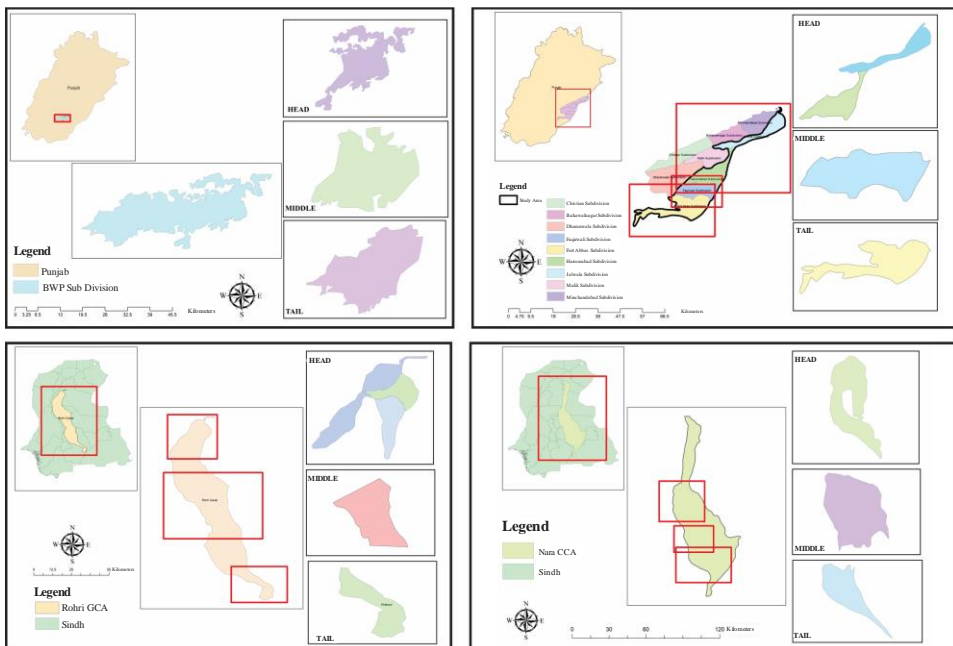
The Punjab irrigation network has shown the head Suleimanki and Islam command area (Upper Left and Right). Head Suleimanki command area, where the PIM reform was introduced, whereas head Islam command area under the provincial irrigation department of Punjab. The Sindh irrigation network has shown the Nara and Rohri command area (Below Left and Right). Nara command area, where the PIM reform was introduced, whereas Rohri command area under the provincial irrigation department of Sind

The real evapotranspiration was calculated using the SEBAL single-source energy balance model. It was a tried-and-true, widely-used technique for calculating real ET (Bastiaanssen, 1995; Bastiaanssen, et al. 1998; Allen, et al. 2007; Glenn, et al. 2011; Jia, et al. 2011; Liou and Kar, 2014). Incorporating the energy balance utilising some land surface parameters, such as albedo, net radiation, canopy cover, surface temperature, and leaf area index, is the direct empirical technique known as SEBAL. The basis for remote sensing-based ET estimate is provided by the surface energy balance equation.

$$Rn = LE + H + G$$

Where,

Rn is the net radiation,
LE is the latent heat exchanges,
H is the sensible heat, and
G is the soil heat flux

Energy balance may be utilised to identify the decrease in ET brought on by water scarcity. The accuracy of the ET calculations from this approach can be increased using other models. But only if the local level interpolation and calibration of these models were done appropriately. For this investigation, the USGS Earth Explorer was used to obtain the cloud-free MODIS sceneries from January 2015 to December 2021. During this time, estimates of the seasonal real ET were made for both the Rabi and Kharif seasons.

2.3. Performance Indicators

For the comparative examination of the chosen PIM and Non-PIM canal command regions, many performance metrics were employed. Comparing a system's performance over time, comparing its performance in different regions, and allowing comparisons between other systems at various spatial scales were all goals of employing comparative indicators (Molden, et al. 1998). Indicators of performance assist in identifying variations in performance between schemes, seasons, and irrigation sources (Kloezen, 1998). Finding the holes in management policies is also helpful. Performance indicators were not cost-effective and data-intensive, in contrast to process indicators (Kloezen, 1998). We choose to employ the comparative performance indicators suggested by IWMI due to the complexity of the process indicators and their calculation (Molden, et al. 1998). The literature (Murray-Rust and Snellen, 1993; Rao and Rao, 1993; Kloezen, Garcés-Restrepo and Johnson III, 1997; Vermillion, 1997; Dermenc, Büyükcangaz and Kucu, 2003; Hasan, 2004; Cuamba, 2016; Efriem and Mekonen, 2017) cites various scales at which these performance indicators were most. Below is a list of the chosen performance indicators with a brief demonstration.

Cropping Intensity (CI %) = Actual Cropped Area/Gross Command Area

Adequacy of Canal Water Supplies = Average Seasonal Evaporative Fraction

Reliability of Canal Water Supplies = Coefficient of Variation (CV) of Evaporative Fraction

Head to Tail Ratio CI = CI of Head Command Area/ CI of Tail Command Area

Water Productivity (Rs/m^3) = Gross Return/Actual Evapotranspiration (ET$_{act}$)

Gini Coefficient of Agricultural land productivity

Output per Unit of Command Area (Rs/acre) = Net Return/Command Area Irrigated

2.4. Land Use/Land Cover Classification

Using LandSat8 and Sentinel-2 data with 30 and 10-meter resolutions, respectively, LULC categorization for the chosen locations was done. The Earth exploration website provided the satellite visualisation used in the TIFF data output (The US Geological Survey, 2014). From 2015 through 2021, the satellite picture was gathered during the Kharif and Rabi crop seasons. On Top of Atmosphere, the digital quantities were converted into reflectance values (TOA). Later on, a value comparison was used to identify the spectral and textural features. Picture characteristics from the Sentinel-2 image were also delineated for the calculation of cropped area in the research region. The research took into account the spectral, textural, and direct image reflectance properties of the satellite images. Moreover, one index computed as Normalised Difference Vegetation Index (NDVI), and their mathematical expressions are given below:

$NDVI = NIR\text{-}RED/NIR\text{+}RED$

Where NIR is near the infrared and red band. NDVI classified different land objects as:

Class	NDVI Range
Water	-0.28-0.015
Built-up	0.015-0.14
Barren Land	0.14-0.18
Shrub and Grassland	0.18-0.27
Sparse Vegetation	0.27-0.36
Dense Vegetation	0.36-0.74

We estimated the cropped area using NDVI values greater than or equal to 0.2. Beginning in this range, the cultivated area changed based on crop development stage and canopy type. To properly compare the cropping intensity for a time series spanning 2015–16–2021–22, we used the same timeframe for the Kharif and Rabi seasons.

Cotton, sugarcane, rice, bananas, mangos, fallow land, water, forests, built-up areas, etc. are some of the several categories for the LULC. For the categorisation of a satellite picture, a supervised classification method (maximum likelihood) was used (Elbeltagi, et al. 2021; Reddy, Patode, Nagdeve, Satpute, & Pande, 2017; Reddy, et al. 2017). The signature file was made using the same image feature dataset as a classification input (Le

Cam, 1990; ESRI, 2012). An iterative technique was used for every region. In the initial phase, every cell in the region was categorised. Second, the classification has been fully visualised, the signature file has been changed, and the classification is complete or approved (Reddy, et al. 2017). The visual inspections were conducted using Google Earth and Sentinel high-resolution satellite pictures (where applicable). The field survey and plot survey were used to cross-check the features. The same LULC categories as on the map have been assigned to these maps. In Fig. 3, the chosen approach was displayed.

Fig. 3. Flow Chart of Methodology
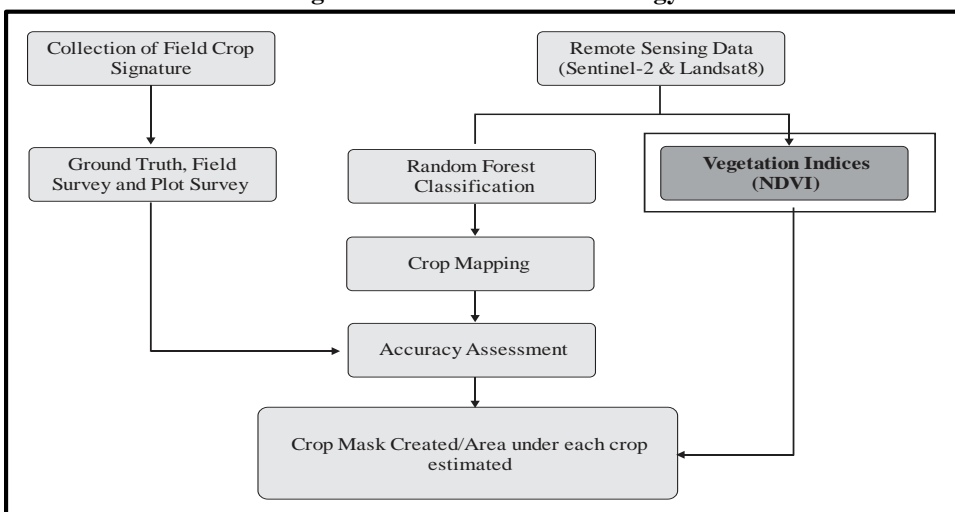
3. RESULTS AND DISCUSSION

3.1. Land Use/Land Cover Classification Change

After categorisation, eight LULC classes were achieved: banana, cotton, rice, sugarcane, fallow land, water bodies, built-up, and mango. Table 1 displays the accuracy of the producers and users for various classes. The user and producer accuracies of the confusion matrix were investigated. The entire accuracy of the image classification was assessed using the categorised picture. The user's accuracy (UA), producer's accuracy (PA), overall accuracy (OA), and Kappa Coefficient were used to quantify the correctness of LULC maps, respectively (Lizarazo, 2014; Pande, et al. 2021; Rossiter, Furey, McCarthy, & Stengel, 2020).

$$\text{User's Accuracy (UA)} = n_{ii} / n_{irow}$$
$$\text{Producer Accuracy (PA)} = n_{ii} / n_{icol}$$
$$\text{Overall Accuracy (OA)} = 1/N \text{ Summation } n_{ii} * 100$$
$$\text{Kappa Coefficient} = \text{Overall Accuracy-Random Accuracy} / 1\text{-Random Accuracy}$$

The total precision for the Nara and Rohri canal commands is 93 percent and 95percent, respectively. For both the canal command, the Kappa coefficient value is greater than 90, which is regarded as a good categorisation category. The capacity to distinguish between land and sea is high. Because they were big, numerous, and more distinct from

the other classifications, the mango and banana fields were simpler to classify. Due to their low NDVI values, the water bodies and rice cells were challenging to distinguish. The reflectance range was the same for cotton fields, fallow land, and both.

Table 1

Accuracy Assessment of Land Use/ Land Cover Classification for Rohri and Nara Command Area

LULC Classification	Nara Canal Circle		Rohri Canal Circle	
	Producer Accuracy (%)	User's Accuracy (%)	Producer Accuracy (%)	User's Accuracy (%)
Banana	66.67	100	100	100
Cotton	100	100	94.44	100
Rice	100	88.89	90	90
Sugarcane	100	90.91	92.86	100
Fallow Land	92.31	100	83.33	83.33
Water	83.33	100	100	92.31
Built-up	100	90.91	92.31	85.71
Mango	80	100	N/A	N/A
Overall Accuracy	95.05		93.33	
Kappa Coefficient	0.94		0.92	

The total precision for the Nara and Rohri canal commands is 93 percent and 95 percent, respectively. For both the canal command, the Kappa coefficient value is greater than 90 percent, which is regarded as a good categorisation category. The capacity to distinguish between land and sea is high. Because they were big, numerous, and more distinct from the other classifications, the mango and banana fields were simpler to classify. Due of their low NDVI values, the water bodies and rice cells were challenging to distinguish. The reflectance range was the same for cotton fields, fallow land, and both. This inequity led to an economic inequity between the head and tail reaches of the canal system and was estimated as the Gini coefficient.

3.2. Comparative Performance of PIM and Non-PIM Irrigation Schemes

Comparative performance analysis of different canal irrigation schemes is a way to improve canal or basin-scale water regulation. Since the 19th century, after the scaling up of irrigation schemes, a wide range of literature has been produced to measure these irrigation schemes, productivity, and efficiency in many ways. Hence, to assess the productivity and efficiency of these irrigation schemes, different indicators/indices were designed based on the nature of data availability. Initially, these performance indices methodologies relied on traditional survey approaches and canal-level data measurement through a rating scale. These data collection methods' accuracy was compromised under different conditions and contexts. Water resource specialists came up with different ways where this data scarcity and collection-related subjective biases could be minimised objectively.

After advancements in remote sensing techniques and free access to better temporal and spatial resolution scale remote sensing data, the use of these datasets became popular

among researchers to better assist traditional data collection methods. Different irrigation schemes' performance can be compared from different perspectives, like distributional equity, efficiency in resource use, and environmental sustainability. In this section, our focus remains on distributional equity, and its consequences resulting in agricultural economic return inequity. In the following section, we discuss section-wise results.

3.2.1. *Cropping Intensity Comparison*

Annual cropping intensity was estimated through crop reported in a distributary level main survey and remote sensing approach using NDVI as a proxy indicator to estimate the overall area under crop in each season. Remote sensing analysis was performed at the subdivision scale, whereas in the main survey, we selected the distributary in each subdivision. To compare canal performance, we estimated the cropping intensity ratios at three scales, i.e., head-to-tail, middle-to-tail ratio, and overall-to-tail ratio, and compared the canals from the equality lens. A cropping intensity ratio indicator equal to one means perfect equity. However, if the value is greater than one, it means the head section is a more cropped area as compared to the tail section. Similarly, if the value is less than one then the tail section is a more cropped area as compared to the head section. Head-to-tail inequality in the canal system largely has two reasons. The first is a technical reason. As the canal approaches the tail, its system losses increase, which ultimately negatively impacts the tail section, generally termed as inequality due to the canal system, i.e., hardware problem. The second reason is the mismanagement of the canal schedule favouring the head/tail section or any targeted area. It is generally termed the software problem (Power Asymmetry) of the canal system. Keeping the above scenario in mind, we used a 20 percent plus/minus uncertainty level as a permissible limit.

Data analysis suggests that the Rohri canal has more inequity between head and tail reaches than the Nara Canal area in Sindh. In the Punjab, the difference in cropping intensity between head and tail reaches remained largely within the permissible limits. The reason for this apparent equality relies on the conjunctive use of the saline and marginally fresh groundwater at the head, middle, and tail sections of the canal. We analysed the estimated evaporative fraction data to validate these initial findings further.

Fig. 4. Comparison of Cropping Intensity Estimated at Distributary and Sub-division Scale
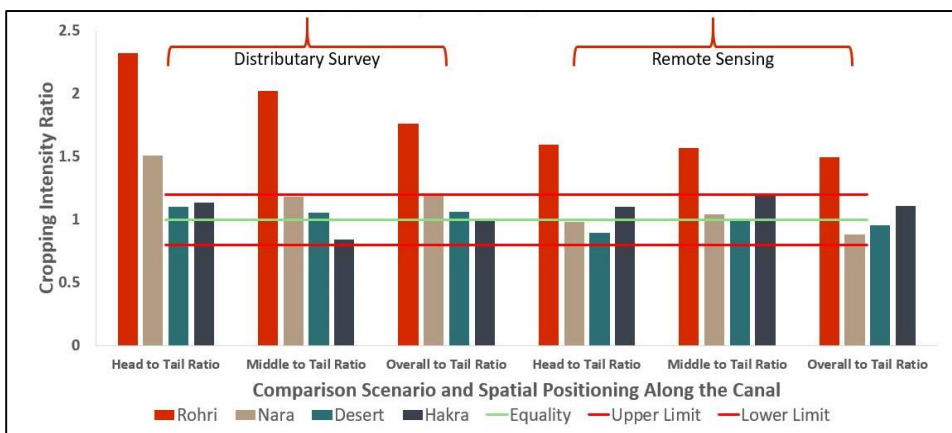
3.2.2. *Adequacy and Reliability of Water Supplies*

Figure 5 provides the adequacy of the canal water supplies in the selected canal command area and the canal system's spatial position. Adequacy is defined in this study as the average seasonal evaporative fraction, and reliability is the temporal variability or the temporal coefficient of variation of the evaporative fraction across a season. Evaporative fraction levels of 0.8 or greater suggest little stress, whereas values below 0.8 indicate increased moisture scarcity due to insufficient water supply. Similarly, lower coefficients of variation indicate a more consistent water supply throughout the growing season (Ahmad, Turral, & Nazeer, 2009).

A comparison of the evaporative fraction for the selected canals shows the seasonal variation of the canal water supplies in each respective command area. During the rabi season, over-allocated canal water from the wheat crop demand, and during the Kharif season, it marginally meets the crop water requirement of the cotton crop. The head, middle, and tail reach variation showed that canal regulation is inadequate and unreliable, and Kharif season water scarcity is easily managed through an existing available water resource with better canal regulation. In the Nara canal, the rabi season canal regulation seems much better than other canal commands simply because the Nara canal has a Chotiari reservoir facility for managing the regulation in a better manner. The length of our canal system is so long that once the water diverts from the source to the canal, there is no storage facility available in the canal system where the water can be stored if it is not needed at the field. During the field investigation, farmers reported this seasonal inadequacy of canal supplies as shown in Figure 6. The investigation showed that due to the over-irrigation of the wheat crop, the wheat yield was hampered.

Farmers adapted to this inadequacy by changing the crop choices to annual crops such as sugarcane and banana (in the case of Sindh), especially in the head and middle reaches. This shifting of crop choices in head and middle reaches due to enough availability of canal supplies indicates huge crises for the tail area in the early Kharif season. Hence, the late sowing of cotton crops reduces the cotton crop yield too. The difference in canal water adequacy and reliability between head, middle, and tail reaches was more significant in Sindh canals than in Punjab canals, as shown in Figure 5.

The foremost explanation for this phenomenon is simply the less variation in the selection of high delta crops in Punjab canals. We observed that the adequacy and reliability difference between head and tail in Punjab is much better than that of Sindh. Can we conclude that canal water distribution in Punjab is equitable as there is less variation between the head and tail reaches of the canal? We hypothesise that the apparent equity in cropping intensity and canal water adequacy/reliability between head-to-tail sections is primarily due to groundwater use. However, this adaptation strategy does not provide an equal agricultural economic return. To validate the above-stated hypothesis, we analysed the land use and land cover classification, and the main distributary level survey-reported agricultural return.

LULC classification reveals that the overall area under cotton crop decreases in both canal command areas of Sindh, with the rate of change in acreage in the cotton crop being 8.7 percent and 7.7 percent in Nara and Rohri canal command areas, respectively. The high delta crops were more visible along the head of the canal network, and as the spatial distance from the main or branch canal increased, the proportion of high delta crops

decreased significantly. The variation in the crop choices for the head section ultimately influenced the low cropping intensity at the tail reaches of the canal system. This situation showed another form of inequity between the head and tail sections. This inequity led to an economic inequity between the head and tail reaches of the canal system and was estimated as the Gini coefficient.

3.3. Water Inequity Leads to Economic Inequity

In the previous section, we analysed different indicators to assess the distributional equity between head and tail sections in different canal systems. Figure 5 provides an overall summary of this section that shows how the land and water productivity estimates per unit and cubic meter of water used differ between the head and tail reaches.

We estimated the annual gross return and net return (Rs.) from the crop production survey at the distributary level. The comparison of the gross and net returns of land productivity (Rs/Acre) shows that the overall desert canal had the highest gross and net returns compared to the other three canals. The head, middle, and tail reach canal comparison show that the Rohri canal middle section had the highest gross return, and the desert canal had the highest net return at the head section. From an equity perspective, Rohri and Nara canals have more variation between head, middle, and tail reaches than the Desert and Hakra canals. Hakra canal has a better annual cropping intensity than Nara and Rohri, but this does not yield better gross and net returns. The higher cropping intensity achieved through the conjunctive use of saline and marginally fresh groundwater compromised the per acre yield of the major cash crop, i.e., cotton, and compromised the land quality due to the continuous use of groundwater for cropping. Other than yield compromise, groundwater use has an economic cost associated with its extraction, which further reduces the net return. Canal water scarcity also confirmed this pattern by examining the Delivery Performance Ratio (DPR) data.

Fig. 5. Summary Results Showing How Distributional Inequity Leads to Economic Inequity
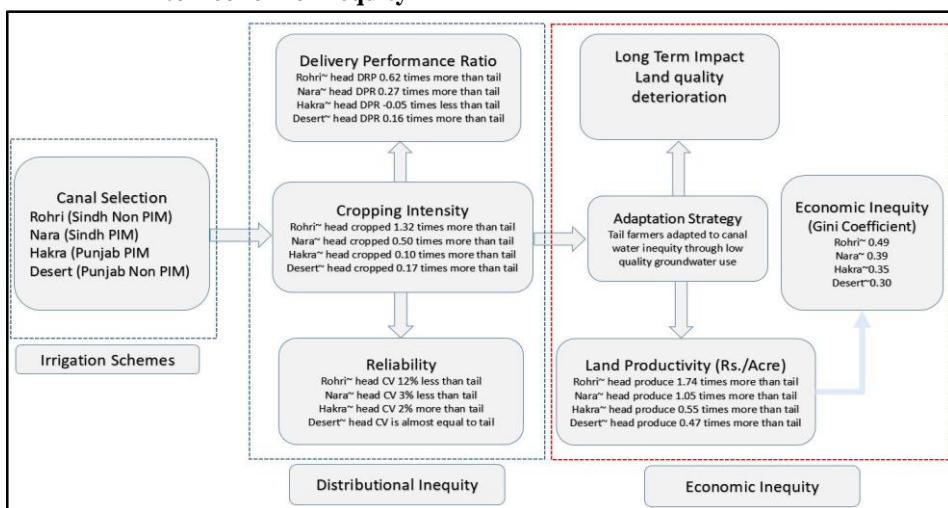
If Nara and Rohri have better DPR than the Hakra canal and even the Desert canal, then why is the gross and net return of Rohri and Nara not exceptionally higher as one would expect? This apparent anomaly can be partially explained by the fact that Nara and Rohri have low cropping intensity due to waterlogging and higher salinity. A low net return of Rohri and Nara canals provides another clue to the grim reality that respondents in both Rohri and Nara canal areas reported in the survey. According to them, due to the poor state of irrigation infrastructure at the tertiary level canal system, the watercourse is unable to deliver the canal water under gravity flow conditions. Hence, even head-reach farmers also need to lift canal water for irrigation, which has an economic cost, thus reducing the net return. Another sharp contrast between the Sindh and Punjab canal systems is that the head and tail distributary land productivity in Punjab is significantly less than in Sindh. The partial explanation for this lower inequity is explained through the percentage difference of higher cash crops at the head reaches, and low cropping intensity at the tail reaches.

Economic Water Productivity (Rs/m3) [EWP] is an indicator of water use efficiency (WUE), widely used for efficiency comparison and also to assess the economic value of water at any desired scale. The World Bank recently estimated the EWP at the provincial level and reported Punjab having an EWP of 0.08 $/m3 for Punjab and 0.06 $/m3 for Sindh (William J. Young, Arif Anwar, Tousif Bhatti, Edoardo Borgomeo, Stephen Davies, William R. Garthwaite III, E. Michael Gilmont, Christina Leb, Lucy Lytton, Ian Makin, 2019). Our estimate at the canal level given in Figure 8, shows that overall, Rohri, Nara, Desert, and Hakra canals had 0.08, 0.12, 0.07, and 0.06 EWPs ($/m^3), respectively. We estimated annual crop water use (m^3) from actual evapotranspiration for the crop water year and used it as a denominator for gross per unit land productivity for the EWP estimate. The difference between our estimated results and the World Bank's results is that they used the provincial level gross return estimates and provincial level crop water use. This comparison provides an interesting insight that Punjab, Desert, and Hakra, being at the tail of the provincial canal network, perform near the provincial average but Sindh, Rohri, and Nara perform above the provincial average, which means that Sindh's remaining irrigation network performs much below the provincial average. Through this economic analysis at the canal and the provincial levels, we were forced to conclude that inequity associated with canal regulation is one of the sources of inequity related to agricultural returns, and this inequity, up to a certain extent, is managed through an improved canal schedule.

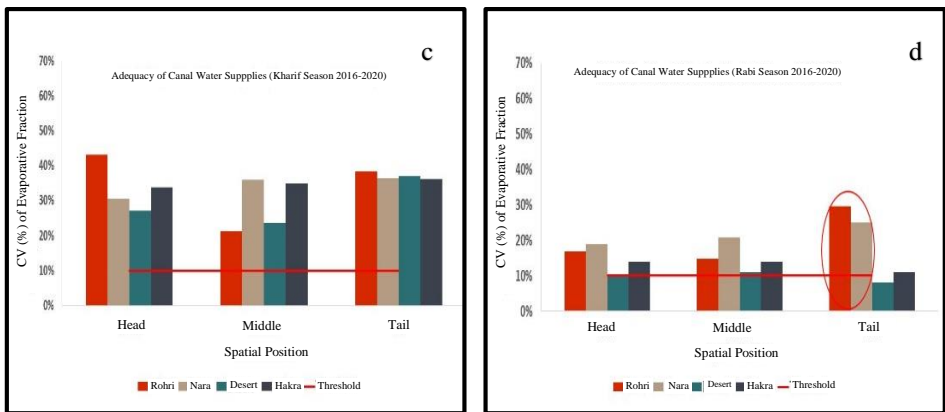**Fig. 6. Adequacy and Reliability in Kharif Season and Rabi Season Measured through Remote Sensing**
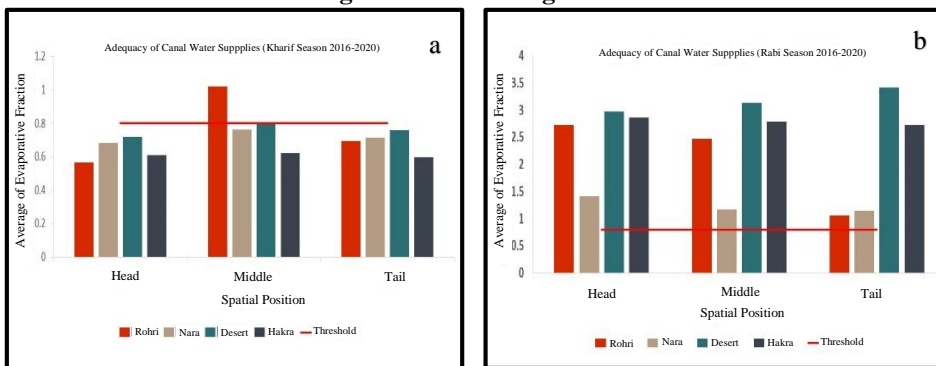
Fig. 7. Adequacy and Reliability in Kharif/Rabi Seasons (a and b) and Changes in Crop Choices (c and d)
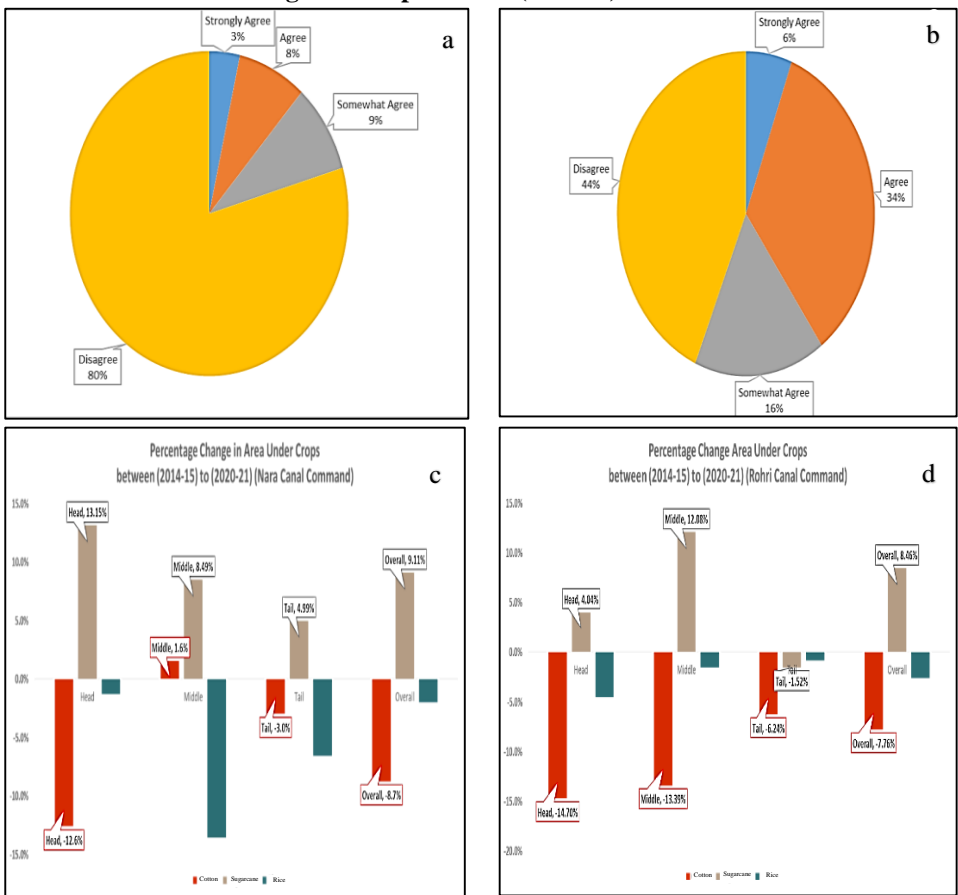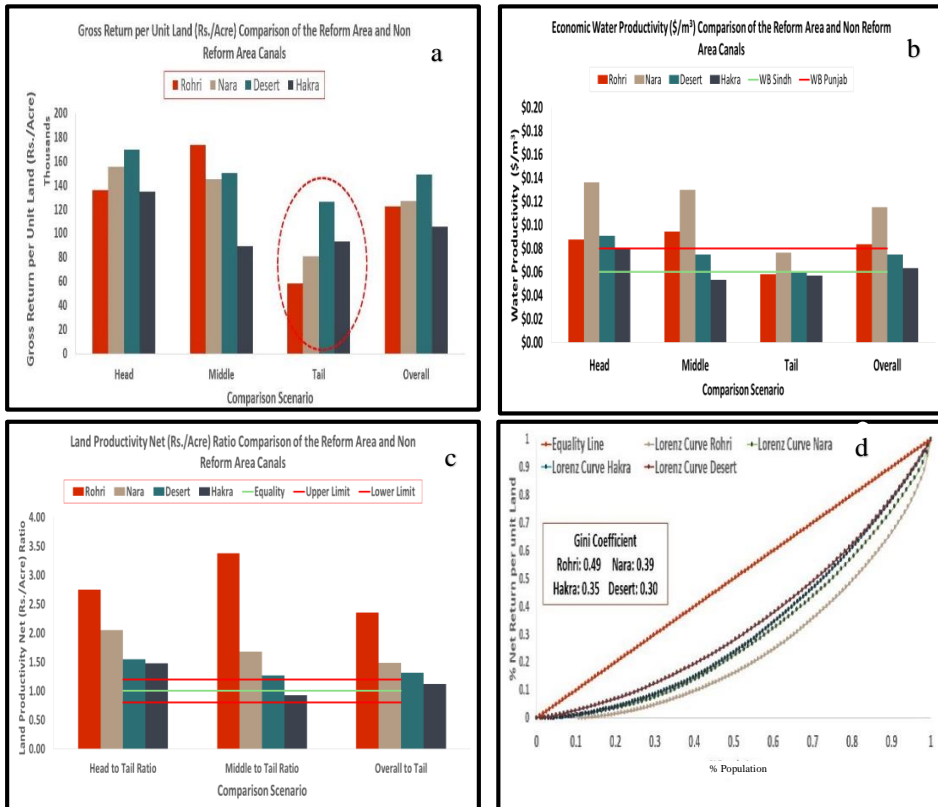
Figure 8. (a) Gross Return per Unit Land (Rs/Acre) Comparision,
(b) Comparison of Water Productivity (Rs./m3) in Selected Canals
at Spatial Position, (c) Net Land Productivity (Rs./Acre)
Ratio Comparison, and (d) Gini Coefficient Comparison
of the Selected Canals

4. CONCLUSION

Based on the quantitative evidence following key conclusions are drawn;

(1) From a head-to-tail cropping intensity ratio perspective, the reform area in Sindh performs better than the non-reform site, whereas, in Punjab, both canals have performed within the permissible limits.

(2) Equity in cropping intensity does not translate into water distribution equity between head and tail reaches of Nara and Rohri canal because the head gets more water for high delta crops than tail reaches.

(3) Overall, the area under the cotton crop is declining in both Nara and Rohri canal commands, and the area under sugarcane is increasing.

(4) The variation in crop choices between head and tail sections leads to inequity in water distribution and agricultural economic returns per unit command area.

(5) Economic inequity is the result of canal water distributional inequity. When compared to Nara, Rohri has more economic inequity, while Hakra has more variation when compared to the Desert canal.

Ethical Approval

Ethical approval for the survey instrument used was taken from the Research Advisory Committee of the US-Pakistan Center for Advanced Studies in Water Jamshoro.

Consent to Participate and Publish

All participants were briefed about the objective and purpose of the research study and written consent was taken before the data collection and to publish the research findings as well.

Competing Interest

All authors declare there is no competing interest

Availability of data and materials

Data used for the analysis of this study available upon request.

Authors Contribution

Conceptualisation: M. Arfan; Formal analysis: M. Arfan, A. Ullah; Writing—original draft: M. Arfan; Review and editing: K. Ansari, Muhammad Ali. All authors have read and agreed to the published version of the manuscript.

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