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Socio-hydrological assessment of water security in canal irrigation systems: A conjoint quantitative analysis of equity and reliability

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ABSTRACT

This paper offers a socio-hydrological assessment of water security that compares canal irrigation entitlements with water deliveries using a conjoint analysis of system reliability and equity. We develop a set of definitions and metrics to quantitatively characterize reliability and equity using newly available datasets of 10-daily canal deliveries from 2007–2017 in the Punjab canal command areas in the Indus Basin Irrigation System of Pakistan, where emphasis has shifted from distributing historically-defined volumetric supplies to improving irrigation efficiencies and crop yields in order to achieve greater aggregate water and food security. Our analysis reveals stagnation and oscillation over time in system-level equity and reliability. We reflect on the potential to positively affect canal irrigation performance and water security through a socio-hydrological approach.

1. Introduction

Framings of water security span a diverse range of approaches that have evolved from an initial focus on the minimum quantity of water available for a given purpose to broader considerations of water access, quality, risk, health and ecological concerns. Recent meta-reviews of the literature on water security reveal that keywords of "irrigation", "food" and "development" feature prominently in content cloud analysis of the literature, along with a variety of research methods and scales [1,2]. While debates and discussions of water security have led to advances in ways of thinking about the issue, experts have noted that, "the majority of academic research on water security is relatively poorly integrated with the needs of policy-makers and practitioners" [3]. There is a gap between conceptual frameworks for studying water security and the pragmatic approaches needed to operationalize and utilize these conceptual developments. While several studies have called for a socio-hydrologic approach to water security [4,5], only a few have shown how that can be applied to irrigation systems [6]. Additionally, in the case of irrigation systems, there is a need for creatively formulated quantitative performance measures to provide an analytical basis for evaluating water security across space and time in a region. We address each of these needs below.

Canal irrigation networks provide vital water supplies for agriculture and food production, and are thus important constitutive elements of water security in regions and times of uncertain or inadequate rainfall [1,7,8]. Irrigation systems are an important determinant of water security, more broadly defined, due to the extensive volumes of water they use, and consequent impacts on communities and the environment [9]. In large irrigation systems, where agriculture can account for 70%-90% of consumptive water use, water allocation systems with effective implementation and governance are important means for enhancing regional water security.

Effective governance, in turn, requires transparency among stakeholders and beneficiaries [9]. Widely used definitions of water security, such as "the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies" [10], have embedded notions of water supply equity and reliability. There is also increasing recognition of the role of governance in socio-hydrologic approaches to water security in river basin management [6].

In the case of canals, water reliability and equity depend both on natural hydrological flows (i.e., in source waters), and also on the infrastructure, access, control, management, and regulations for water deliveries [11]. In these respects, they are jointly social and hydrological, i.e., socio-hydrological [12,13,14]. Reliability of supply in canal networks is of crucial importance as it allows farmers to anticipate and optimally plan for water uses that enhance productivity. Reliability is further defined here as the temporal consistency in supply of irrigation water, and it is largely (though not exclusively) a physical measure. It is

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a measure of temporal expectations. On the other hand, equity is defined here as the spatial consistency of irrigation supply for each canal, as compared with others, and it is thus social as well as spatial. It is a measure of socio-spatial expectations.

In regards to the social dimensions of canal irrigation, it has long been recognized that institutional and social factors are critical [8,15] for addressing challenges of water security, and there is a need for approaches that explicitly link social and hydrological systems [6]. While there is increasing emphasis on quantitative methods in socio-hydrology, few studies have applied that approach to water security in canal irrigation systems [10]. Here, we propose a quantitative socio-hydrologic framework for jointly assessing the reliability and equity of water deliveries to gain a new understanding of water system security as well as performance.

We apply this framework to the Indus basin irrigation system (IBIS) in the Punjab province of Pakistan, building on our earlier work on the socio-hydrology of channel flows [13]. Historically, the large canals of this irrigation system were conceived to provide "protective irrigation" that spread water over extensive areas to provide minimum amounts of water as far as possible, oftentimes leading to conditions of deficit irrigation [16]. This early approach to water and food security provided the minimum "duty of water' required to secure basic levels of production of staple crops such as wheat and pulses, fodder crops, and strategic cash crops like cotton for the mills in Britain [14]. Yields were poor due in part to trade-offs between revenue generation, socio-political control, and famine risk reduction [13]. After independence in 1947, emphasis shifted to increasing the efficiency and productivity of canal deliveries through water storage, dam operations, channel lining, and on-farm water management [17]. This approach to water security was accompanied by greater emphasis on water consuming staple and cash crops such as rice and sugarcane for national and global markets, with adverse feedback on water security [18]. Equity has always been important in Indus basin irrigation management, but it has been treated mainly through qualitative research and political negotiations vis-a-vis quantitative analysis at the canal command level [19].

The existing system in Pakistan remains plagued with significant inefficiencies and deficiencies in control and distribution of surface irrigation water, with increasingly adverse impacts on crop yields and production [18]. The need to improve 'water security' in the country's large irrigation system is important from not only a local standpoint, but also from a larger national agricultural production and food security perspective. In a positive development, the Government of Punjab Irrigation Department has posted canal entitlements and deliveries online to help improve transparency, analysis, and thereby water security [20].

Here, we analyze the extensive network of twenty-five main surface irrigation canals in Punjab, and evaluate their reliability and equity using the newly available data sets of canal 'entitlements' (planned supply) and 'deliveries' (actual supply) over a 2007–2017 decadal time span. In the following sections, we first briefly review recent work on concepts of water security in canal irrigation systems. Next, we survey commonly used performance metrics for surface irrigation systems, and we develop a list of socio-hydrologic metrics that collectively provide a multi-scalar temporal and spatial characterization of system performance. These metrics are used in a case study of the Indus Basin Irrigation system in the Punjab province of Pakistan, where we analyze and interpret differences in reliability and equity among canals. Finally, the key findings of the analysis are presented, along with a discussion of potential applications to other canal systems in future studies.

2. Water security concepts in canal irrigation systems

Surface irrigation systems around the world have been extensively studied and evaluated on several dimensions that include trends and patterns of efficiency and equity. There has been growing focus on linking irrigation system performance with water security and to some extent socio-hydrology [1,11,14,21]. Historically, large canals in the Punjab province of Pakistan were primarily conceived, constructed, and operated with a technocentric approach [22]. This was also the case for other large systems such as in Central Asia [11] and Egypt [23]. The performance of these systems was primarily evaluated along technical dimensions such as efficiency of delivery, canal seepage, bank deterioration, and annual maintenance. Additional measures of performance included efficiency of water use [24] and cost-recovery [25]. As noted above, the technocentric approach had a mix of social, economic, and political controls associated with colonial concepts of water security [16].

Following independence, the focus shifted to technical indices that capture the fraction of water that is used beneficially for crop production from the total water withdrawn (such as withdrawal efficiency, conveyance efficiency and farm delivery efficiency), as well as the crop production benefits of how evenly irrigation water is distributed in a field (distribution uniformity) [24]. The relevant scale and scope of these metrics range from field to watercourse to canal command levels.

Concepts of system-level performance of large canal networks have also been developed. For example, there are studies that compare scheduled and actual deliveries to characterize system adequacy, efficiency, dependability, and equity, and these have been used to study systems in Sri Lanka and Egypt [23] and in Iran [26]. In more recent work, there have been explicit attempts to quantify water security through indices, such as the two-dimensional household-level irrigation water security index (that considers hydrology and governance) for systems in Central Asia [11].

In the case of the canal systems in Pakistan's Indus Basin, a frequently used concept is the Delivery Performance Ratio (DPR), which is the ratio of actual discharge to design discharge of a channel. It has been widely used to judge the performance of channels in the IBIS. Related concepts such as the "relative delivery performance ratio," which is the ratio of the tail DPR to the head DPR of a channel, have also been developed and used as indicators of equity within watercourses [27]. In more recent work, equity has been studied with Gini indices [28], and that approach has been applied to examine tertiary canals in Punjab, Pakistan using outlet discharge data [29], as well as distribution of accumulated wealth [30].

3. New water security metrics for socio-hydrological evaluation of canal irrigation systems: equity, reliability, consistency, and compliance

Building upon the post-colonial approach to irrigation performance and water security, we formulate a set of definitions and metrics that collectively provide a socio-hydrological lens on water security in large-scale irrigation networks. This approach departs from 'index' formulation methods where a set of dimensions and indicators are typically combined to create aggregate water security metrics [11,31], and it is also different from singularly focused approaches where only a hydrological or sociological variable is explored.

We develop a framework for an irrigation network (a set of reservoirs and interconnected canals) where a discrete number of irrigation deliveries are provided to the canals in a period of time. The irrigation deliveries are typically based on canal command 'entitlements' that are based on allocation norms adjusted for forecasted supplies in the region [32,33]. As the entitlements are set at the start of a cropping season, they serve to form expectations of supply. We will interchangeably use the word 'entitlement' and 'expected delivery' or 'expected supply' in the rest of the discussion.

We define α_k^i as a ratio of amount of water delivered (d) to the amount entitled, e, for a canal i for time interval k as:

$$\alpha_k^i = \frac{d_{i,k}}{e_{i,k}} \tag{1}$$

The above formulation is such that $\alpha_k^i = 1$ when entitlement matches with actual (or realized) delivery, and $\alpha_k^i < 1$or > 1 when actual delivery is less than the entitlement or greater than the entitlement, respectively. Also, $\alpha_k^i = 0$ when no delivery occurs at a time of some entitlement, and $\alpha_k^i = \infty$ when a delivery is made while entitlement was zero.

The number of intervals or irrigation supply turns where no water is provided at a time of entitlement during an irrigation season is an important measure. We denote the fraction of missed irrigation turns in a season as:

$$\delta_{i,t} = \frac{I_{i,t}}{T_{i,t}} \tag{2}$$

where $I_{i,t}$ is the number of missed turns when no delivery was provided for canal i in irrigation season in year t,; and $T_{i,t}$ is its total number of irrigation turns scheduled for that season.

Using data of e, d, and parameters α and δ, a series of useful metrics can be constructed based on statistical measures (primarily mean, μ, and coefficient of variation C_v) at different scales and time periods in the system at the canal level and network level.

3.1. Canal level metrics

A brief description of some key metrics for canal level analysis is as follows:

3.1.1. Canal supply consistency (θ^i)

This is the coefficient of variation of α_k^i, and captures the intra-canal variability of delivery to entitlement ratios for the i^{th} canal in an irrigation network. It provides a measure of supply consistency, i.e. how supply (at some fractional level to entitlement) is consistent (or not) within a season in a given canal. When θ^i is small, the canal has high consistency in its delivery to entitlement ratio. For instance, if a canal is supplied irrigation water at 70% of its entitlement ($\alpha_k^i = 0.7$) throughout the season, it has perfect consistency, and $\theta^i = 0$. The 'dependability' metric is similar (in that it measures temporal variation in supply at a location) [23]. The supply consistency metric enables comparability across different canals.

3.1.2. Canal supply reliability (ρ^i)

This is defined as the likelihood of receiving the allocated water entitlement during an irrigation turn [25]. It is computed as the probability of receiving the full entitlement in each period over which the surface supplies are to be provided. This metric captures the extent to which entitlements are met over a season for a canal, while accounting for the discrete irrigation turns. If a canal i receives its full entitlement at every scheduled turn in the season, then $\rho^i = 1$.

3.1.3. Canal entitlement compliance (A^i)

This metric quantifies the fraction at which the aggregate or total entitlement (allocation) for a season for a canal was fulfilled. It accounts for total deliveries made but does not consider the timing of the deliveries. A^i indicates how much the seasonal volumetric supply matches the allocation (even though some deliveries may have occurred at intervals that were different from the intervals of entitlement).

3.2. Network level metrics

The key metrics for network level analysis include measures of equity, where variability in the system across canals is quantified, and reliability. A brief description of these metrics is as follows:

3.2.1. Interval equity (ε_k)

The coefficient of variation of delivery to entitlement ratios (α_k^i) across canals in the network at the kth interval is defined as the interval equity parameter ε_k. This is based on the concept that *spatial variation in performance provides a measure of equity* [23], regardless of the performance level. When variation across canals is low (i.e. $\varepsilon_k$is low) then interval equity is high, and at $\varepsilon_k = 0$, the network is perfectly equitable. Note that interval equity is a measure to capture spatial variability in supply, and is not about what should be delivered, or what is a fair share. Rather, it measures how evenly the locations are served. For instance, if all canals are served at 70% of their entitlements in a time interval, then there is full interval equity, as compared to a case where one canal may be served at 50%, and another canal is served at 90% of their respective entitlements.

3.2.2. Equity (E)

This is defined as the mean ε_k in a season, and serves as a single measure of system equity that becomes useful for comparative analysis.

3.2.3. Consistency equity (CE)

This is defined as the variability of canal supply consistency θ^i across all canals in the network in a season. At perfect consistency equity, all canals will have the same supply consistency, and the value of CE = 0.

3.2.4. Network reliability (NR)

This metric is the mean reliability of all canals in the network. It provides an aggregate measure of reliability at the system (network) level.

3.2.5. Reliability equity (RE)

This is similar to CE, and captures the variability in canal reliabilities in the system. It allows for capturing cases where there may be high overall network reliability, but significant differences between canals may exist. Also, this metric by encapsulating both reliability and equity serves as a conjoint measure for the system.

3.2.6. Network entitlement compliance (A_{sys})

This is the fraction of total deliveries made across all canals in the season to total season entitlement of all canals in the network. It provides an aggregate measure of the extent to which the seasonal allocation to a canal network was fulfilled, but does not differentiate between how the allocations may have varied for different canals. In some cases, it is possible that some canals may have low (under) compliance while others may have 'over' compliance (with deliveries greater than the entitlements), thus making system-level compliance high, but differential compliance at canal level.

3.2.7. Compliance equity (C_pE)

This metric is the coefficient of variation of canal compliances, A^i, and captures the spatial (canal-level) variability.

Table 1 summarizes these metrics for canals, and Table 2 summarizes the metrics for a system of N canals (network) that are supplied with surface irrigation deliveries in a total of T discrete intervals in an annual cropping season.

This set of metrics provides a dual framing where equity related metrics are spatial variations of performance metrics, such as reliability and compliance. The compliance and to some extent the consistency and reliability metrics are strongly dependent upon, but not determined by, hydrological inflows to the basin that affect water availability in a season. Conversely, the equity measures are driven more by planning and operations decisions (i.e. social processes), though they too may be affected by hydrologic variability.

These measures are simple statistics that have important social implications for regions economically dependent on irrigation supplies for agricultural production. Large commercial farms and rich farmers are more likely to have the capacities to deal with variability in irrigation water supply, while poor consumers and subsistence farmers face more dire consequences [11]. These metrics (summarized in Tables 1 and 2) collectively can help build a nuanced socio-hydrological characterization of water security, reveal trends in system performance,

Table 1
Metrics applicable at canal level.

Irrigation interval – k [days]	Season [annual]	Multi-year
1. Delivery to entitlement ratio for i[th] canal at k[th] interval: $\boldsymbol{\alpha_k^i = \frac{d_{i,k}}{e_{i,k}}}$	1. Canal Supply Consistency: $\theta^i = C_v(\alpha_k^i) = \frac{\sigma(\alpha_k^i)}{\mu(\alpha_k^i)}$ This is intra-canal supply variability 2. Canal Supply Reliability: $\rho^i = \frac{\sum_{k=1}^{T}\min(1,\alpha_k^i)}{T}$ This is likelihood of receiving full supply at time of entitlement 3. Fraction of missed irrigation turns in a season: $\delta_{i,t} = \frac{I_{i,t}}{T_{i,t}}$ 4. Canal Entitlement Compliance: $A^i = \frac{\sum_{k=1}^{T} d_{i,k}}{\sum_{k=1}^{T} e_{i,k}}$	1. $X^i = C_v(A_t^i) = \frac{\sigma(A_t^i)}{\mu(A_t^i)}$ *t* denotes year. This is inter-year variability in canal compliance

*σ is standard deviation, μ is mean, C_v is coefficient of variation.

and identify targets for management and policy intervention.

4. Indus Basin irrigation system (IBIS) in Punjab

The infrastructure of the IBIS is hierarchically structured. Water is diverted from rivers into main canals that subdivide into branch canals, distributary canals, minor canals and individual village watercourses. This large network is operated through a proportional system of water deliveries that have evolved over more than a hundred years. At the local level, the IBIS also operates as a "supply-based system" in which fixed water outlets receive their share of water on rotation (*warabandi*) [29]. This is in contrast to demand-based systems where farmers place requests for water based on crop requirements. Irrigators rely upon tubewell withdrawals to supplement surface water deliveries which increases production costs [34].

In a supply-based system such as the IBIS, the reliability of water delivery assumes a particularly salient role in defining system performance. The operational design of allocations to farmers (based on farm size and soil conditions) was motivated in part by social equity [29,35]. This emphasis continues in the modern ethos of the management agencies of the IBIS where equity and reliability are both considered important [22].

To date, canal-level management in the IBIS has focused largely on ensuring delivery of the total seasonal volumetric entitlements to irrigators, and performance measures have traditionally emphasized "losses" (evaporation, seepage, and theft) in the system. These measures have so far proven inadequate as critical knowledge gaps remain, and issues of variation in reliability and inequitable performance persist. In this context, we employ our framework to examine how equity and reliability in the IBIS in Punjab measure up and how these attributes of the system have been evolving.

We use data of main canal deliveries provided through the information portal of the Punjab Irrigation Department [20]. The dataset used in this work spans eleven years from 2007 to 2017 and consists of 10,125 records. It includes total season volumetric entitlement in Million Acre Feet (MAF), 10-daily entitlement as flows in cubic feet per second (cusecs), as well as 10-daily deliveries as flows in cusecs for twenty-five major canals in the Punjab province. The reliability of individual canal deliveries is assessed by comparing entitlements and deliveries over time, which may vary with river inflows into the system but should otherwise be consistent over time.

The twenty-five canals in Punjab are organized in two 'zones' (Table 3). The first is the Indus zone where the Tarbela dam and storage reservoir and downstream barrages located on the main stem of the Indus river serve twelve canals. The second is the Jhelum-Chenab zone comprising of the tributary rivers of Jhelum and Chenab that serve thirteen canals. A specific feature of this zone is that four of its thirteen canals are served by Marala barrage on the Chenab River and are not connected to a storage reservoir in Pakistan. The other nine canals are directly or indirectly linked to the Mangla dam and storage reservoir situated on the main stem of the Jhelum river, which should provide greater reliability (Fig. 1).

Table 2
Metrics applicable at network level.

Irrigation interval – k [days]	Season [annual]	Multi-year
1. Interval Equity (at k[th] interval for network): $\boldsymbol{\varepsilon_k = \frac{\sigma(\alpha_k^i)}{\mu(\alpha_k^i)}}$ 2. Fraction of canals with missed irrigation turns at k[th] interval: $\boldsymbol{\frac{[\sum_{i=1}^{N} I_i]_k}{N}}$ 3. Fraction of system entitlement fulfilled at k[th] interval: $\boldsymbol{A_{sys,k} = \left(\frac{\sum_{i=1}^{N} d_i}{\sum_{i=1}^{N} e_i}\right)_k}$	1a. Equity: $E = \mu(\varepsilon_k) = \frac{\sum_{k=1}^{T}\varepsilon_k}{T}$ 1b. Consistency Equity: $CE = C_v(\theta^i) = \frac{\sigma(\theta^i)}{\mu(\theta^i)}$ 2a. Network reliability: $NR = \mu(\rho^i) = \frac{\sum_{i=1}^{N}\rho^i}{N}$ 2b. Reliability equity: $RE = C_v(\rho^i) = \frac{\sigma(\rho^i)}{\mu(\rho^i)}$ 3a. Mean fraction of missed irrigation turns: $\Gamma = \frac{\sum_{i=1}^{N}\delta_{i,t}}{N}$ 3b. Missed irrigation turns equity: $IE = C_v(I_{i,t}) = \frac{\sigma(I_{i,t})}{\mu(I_{i,t})}$ 4a. Network Entitlement Compliance: $A_{sys} = \frac{\sum_{i=1}^{N}\sum_{k=1}^{T} d_{i,k}}{\sum_{i=1}^{N}\sum_{k=1}^{T} e_{i,k}}$ 4b. Compliance Equity: $C_pE = C_v(A^i) = \frac{\sigma(A^i)}{\mu(A^i)}$	1. Inter-year variability in system entitlement compliance: $A_{sys,t} = C_v(A_{sys})_t$

Table 3
Main canals and command area in irrigation network of Punjab, Pakistan.

Index [Label]	Canal Name (Abbreviation)	Storage Reservoir/Zone	Culturable Command Area (CCA)* [Million Acres]
1. [1T]	Thal Canal Main Line Upper (Thal)	Tarbela / Indus	1.912
2. [2T]	Chasma Right Bank Canal (CRBC)	Tarbela / Indus	0.35
3. [3T]	Rangpur Canal (RangC)	Tarbela / Indus	0.345
4. [4T]	Haveli Interlink (H-INT)	Tarbela / Indus	0.0117
5. [5T]	Sidhnai Canal (SidC)	Tarbela / Indus	0.872
6. [6T]	Pakpattan Canal Lower (PakPL)	Tarbela / Indus	1.049
7. [7T]	Lower Mailsi Canal (LMC)	Tarbela / Indus	0.994
8. [8T]	Lower Bahawal Canal (LBaha)	Tarbela / Indus	0.73
9 [9T]	Muzaffargarh Canal (Muz)	Tarbela / Indus	0.82
10. [10T]	D.G. Khan Canal (DGK)	Tarbela / Indus	0.906
11. [11T]	Punjnad Main Line -including Abassia Link Canal (Punj)	Tarbela / Indus	1.355
12. [12T]	Abbassia Canal (Abbas)	Tarbela / Indus	0.154
13. [1N]	Marala Ravi Interlink (MR-INT)	None / Jhelum- Chenab	0.158
14. [2N]	Upper Chenab Canal Interlink (UCC-INT)	None / Jhelum- Chenab	1.441
15. [3N]	Central Bari Doab Canal (CBDC)	None / Jhelum- Chenab	1.67
16. [4N]	Upper Depaulpur Canal (UDC)	None / Jhelum- Chenab	0.35
17. [5M]	Upper Jhelum Canal interlink (UJ–INT)	Mangla / Jhelum- Chenab	0.544
18. [6M]	Lower Jehlum Canal (LJC)	Mangla / Jhelum- Chenab	1.518
19. [7M]	Lower Chenab Canal (LCC)	Mangla / Jhelum- Chenab	3.054
20. [8M]	Lower Bari Doab Canal (LBDC)	Mangla / Jhelum- Chenab	0.659
21. [9M]	Lower Depaulpur Canal (LDC)	Mangla / Jhelum- Chenab	0.612
22. [10M]	Upper Pakpattan Canal (UPak)	Mangla / Jhelum- Chenab	1.049
23. [11M]	Fordwah Canal (FC)	Mangla / Jhelum- Chenab	0.428
24. [12M]	Eastern Sadiqia Canal (ESadiq)	Mangla / Jhelum- Chenab	1.052
25. [13M]	Upper Bahawal interlink and Qaim Canal (UBQ-INT)	Mangla / Jhelum- Chenab	0.772

* *Data Sources:* Ref. [36] chapter 5, Table 18, and Ref. [21] Table 2.4. CCA for Lower Mailsi and Upper Bahawal estimated from data of other canals. Greater Thal Canal is not included here as its data commences from 2014 and does not span the full period of analysis.

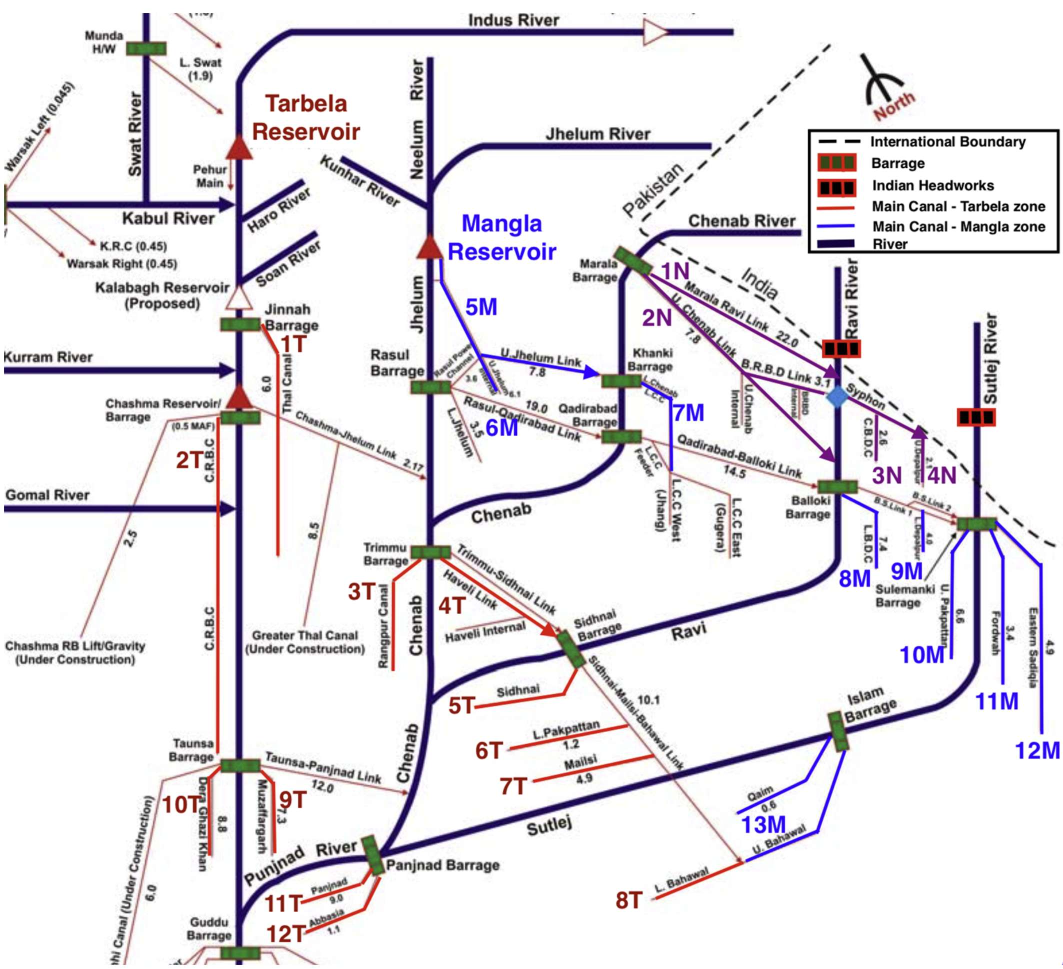

Fig. 1. A schematic of the Indus Basin Irrigation System located in Punjab and neighboring Khyber Pukhtunkhwa (KPK) province. The twenty-five canals supplying water from Tarbela and Mangla reservoirs are labeled with suffix T and M respectively. Upstream canals in the Jhelum-Chenab zone that are not linked to any storage reservoir in the country are labeled with suffix N and marked with purple arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

There are two cropping seasons in Pakistan: Kharif (summer) that runs from April through September and is the major production season; and Rabi (winter) that spans from October through March. Major Kharif crops include cotton, rice, sugarcane, and maize. Wheat is the major Rabi crop, followed by gram, tobacco, rapeseed, barley and mustard. Punjab has five agro-climatic zones (ACZs). The eastern part of the province under the Jhelum River supports crop mixes known as Punjab Rice-Wheat, Punjab Sugarcane-Wheat, and Punjab Cotton-Wheat zones. They are water intensive and receive higher monsoon rainfall. Indus river canals serve ACZs with somewhat drier Punjab Cotton-Wheat and Punjab Mixed Wheat cropping patterns. These patterns prove relevant when canal reliability and equity are examined.

The Indus and its main tributaries (Kabul, Jhelum, Chenab, Ravi, Sutlej and Beas) have flows that rise in early summer with the snowmelt and monsoon rainfall and have peak discharge in July or August. The mean monthly flows during November to February (in the Rabi season) are about a tenth of those in summer. Based on the Indus Water Treaty, Pakistan uses waters of the Indus, Jhelum, and Chenab rivers, while flows of the Ravi, Sutlej and Beas have been allocated to India. The Indus has large seasonal fluctuation in flows. On average, 75 percent (67 MAF) of the total annual mean discharge (of 90 MAF) occurs in four Kharif months of June to September. The mean annual flow of the Jhelum and Chenab rivers combined is 49 MAF, of which 65 percent (31 MAF) occurs in four months from May to August – one month earlier than the Indus [36].

The surface canals supply irrigation water for cropping in Kharif and Rabi seasons for over 15 million hectares (~ 37 million acres) in Punjab [37]. Each year, seasonal forecasts of water availability are made based on reservoir storage levels and expected inflows. These forecasts are then used for making specific canal allocations (i.e., season entitlements) based on their shares according to the country's 1991 Water Apportionment Accord [33]. The canals' total allocations in MAF and entitlements for 10-day flows in cusecs are specified at the beginning of each season, and actual deliveries are recorded over the course of the irrigation season (Fig. 2). In terms of equity, irrigators would expect, first, that the two zones would each receive their proportional shares, and second, that canal commands within each zone would receive their respective shares.

4.1. Stability of supply: Missed and unscheduled deliveries

A key issue in performance of the IBIS is missed deliveries that serve as a basic measure of reliability. Previous studies have shown that missed surface water deliveries appear to be the largest cause of losses for farmers. Some cases, such as watercourses in the lower riparian province of Sindh, have 14% to 55% missed turns in an irrigation season [35]. Farmers typically do not receive any monetary compensation for lost delivery turns, and therefore the randomness and frequency of missed deliveries depress yields and returns for farmers.

The problem of missed delivery turns has been documented in the smaller tertiary canals and watercourses; however, it has previously not been investigated for the major twenty-five canals in Punjab. Our analysis of the canal deliveries data shows that missed deliveries ($I_{i,t}$) are manifested at the major canals, which ultimately lead to missed deliveries at the water-course scale, thereby affecting farm-level supply. Fig. 3 shows $I_{i,t}$ for each canal (bottom plots) for Kharif and Rabi seasons, and it is observed that $I_{i,t}$ in the worst cases is double for Rabi as compared with Kharif. Additionally, some canals exhibit repeated patterns of high $I_{i,t}$ such as Rangpur canal in Rabi and Marala-Ravi interlink, D. G Khan and Muzaffargarh canals in Kharif. These problems are in part a function of lower and less reliable river inflows during the Rabi season.

In addition to examining missed deliveries, we also counted 'unscheduled' deliveries, i.e. those cases when an entitlement in a 10-day interval was zero, but a delivery was made. The top row plots in Fig. 3 show the number of unscheduled deliveries for Kharif and Rabi seasons for each canal. In this case, Fordwah canal in Rabi season stands out with consistently high (ten to fifteen) counts of unscheduled deliveries year after year. In comparing between seasons, Rabi exhibits higher instances of unscheduled deliveries as compared to Kharif where such occurrences appear to be rare. For a gross comparison, in the Kharif season there were 3.7% (183 out of 4950 records) of missed deliveries during the eleven-year period across all the twenty-five canals. In Rabi season, there were 5.7% (292 out of 5110 records) missed deliveries during this period. Furthermore, there were also more unscheduled deliveries, 8.6% in Rabi as compared to 0.7% for Kharif. Overall, 14.3% deliveries in Rabi and 4.4% deliveries in Kharif did not match their planned schedule that was set at the beginning of each season. In contrast with missed deliveries, unscheduled deliveries cannot be a function of river inflows, as adjacent canals have not had similar benefits, which raises issues of equity as well as reliability.

The plots in Fig. 3 also show that for some canals there is a recurring mismatch of deliveries and entitlements year after year. It appears that there is no trend of adjusting canals entitlements and deliveries based on past experience. The results indicate a need for improving the delivery scheduling process in order to reduce missed and unscheduled deliveries in the irrigation network. These results may be due to historical canal entitlements that cannot be practically fulfilled due to

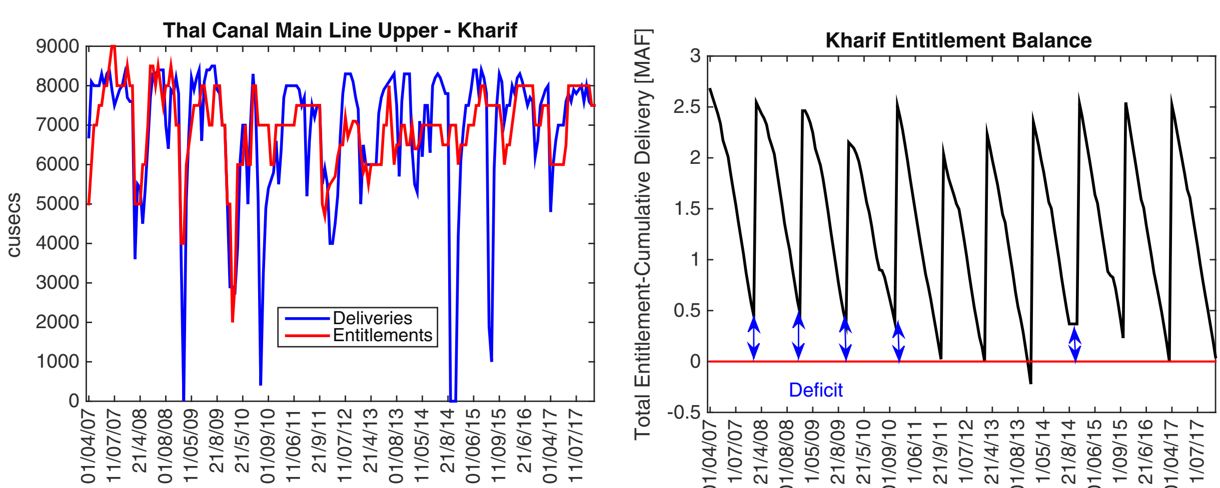

Fig. 2. Left: Irrigation entitlement (red) and actual deliveries (blue). Right: Total entitlement balance reported in 10-day intervals. Data shown is for Thal Canal for Kharif seasons 2007–2017. Several years show repeated deficits where cumulative delivery was less than total entitlement for the season. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

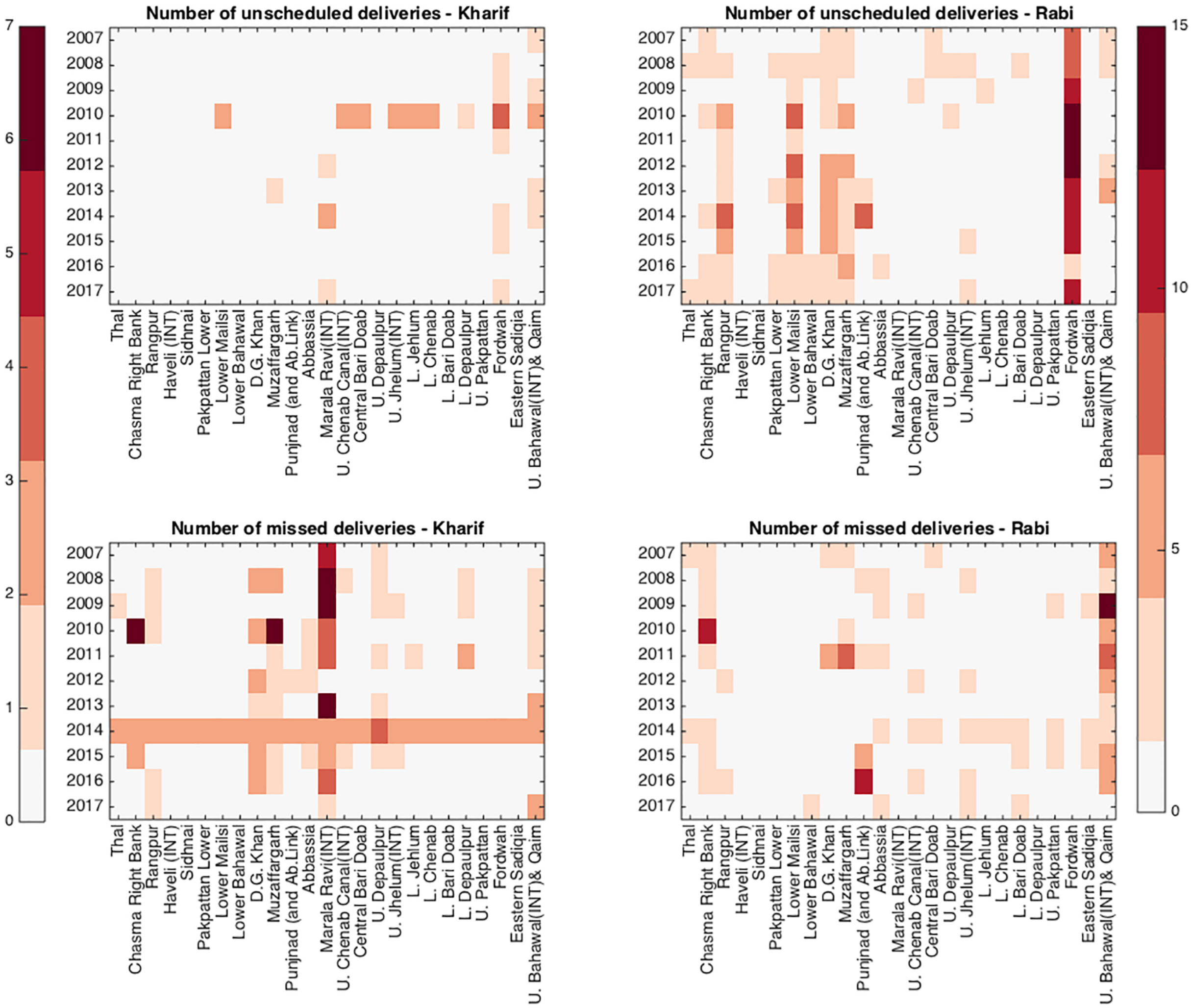

Fig. 3. Above: Number of unscheduled deliveries (cases of deliveries under zero entitlement in a period). Below: Number of missed deliveries, $I_{i,t}$ (cases of no delivery at times of entitlement). Note color bar axis is different for plots on the left (Kharif) and right (Rabi).

their specific geographical, hydrological, and design related factors. Such entitlements may be maintained as paper rights with the tacit understanding that they may be fulfilled during years of surplus flows and have better prospects in the event of increased storage. In such cases, it is useful to consider the consistency metric, θ^i, which indicates how supply at some fractional level to entitlement is consistent (or not) at each interval within a season.

4.2. Canal supply consistency and compliance

The canal supply consistency, θ^i, is useful to get a measure of predictability for a canal while accounting for systemic factors that may make serving a specific entitlement challenging. Consider a case, where a canal is only delivered 80% of its stated entitlement. If it is done so consistently throughout the season, then the θ^i will have a small value (and consistency will be high). High consistency gives a level of predictability for water users and allows for better planning.

Fig. 4 shows θ^i for the Kharif season for canals ordered from upstream to downstream locations in each zone on the x-axis. The median supply consistency, shown as a black square marker, has an increasing trend. These results indicate that the variability generally increases for downstream canals, which is analogous to well-documented head-tail inequities at the smaller distributary and watercourse scales[29,35]. It is also the case that cropping patterns have declining water requirements from upstream to downstream commands, which raises questions about whether that reflects an adaptation to less reliable and less equitable deliveries. It may also be noted that the four upstream canals in the Mangla zone, which are not linked to a storage reservoir, exhibit higher variability than the canals that are linked to the reservoir, which makes sense. These four canals are Marala-Ravi interlink, Upper Chenab interlink, Central Bari Doab, and Upper Depalpur canal. Another important feature in the plot is that there is a fair amount of spread in the year-to-year supply consistency. The canals that exhibit highest consistency (lowest values of θ^i) are Thal canal, an upstream canal that branches from the Indus main stem, and Lower Jhelum and Lower Chenab canals that are upstream canals in the Mangla zone. A notable exception from the trend of increasing θ^i from upstream to downstream (moving left to right on the x-axis) is the Eastern Sadiqia canal in the Mangla zone. This canal has been extensively instrumented, monitored, and studied for the past few decades [29,38,39], and this focus may contribute to its more reliable but possibly less equitable record of deliveries.

The data for θ^i allows for hypotheses about how farmers form expectations about canal irrigation supplies and respond in various ways. For instance, in a system where actual supply may be routinely less than the entitlement (i.e. low θ^i and high consistency) the farmers are likely to adapt and plan accordingly in contrast to cases where θ^i is high (low consistency), which may discourage farmers from making investments under uncertainty. If θ^i changes from year to year as appears to be the case here, the surface irrigation system is particularly challenging to

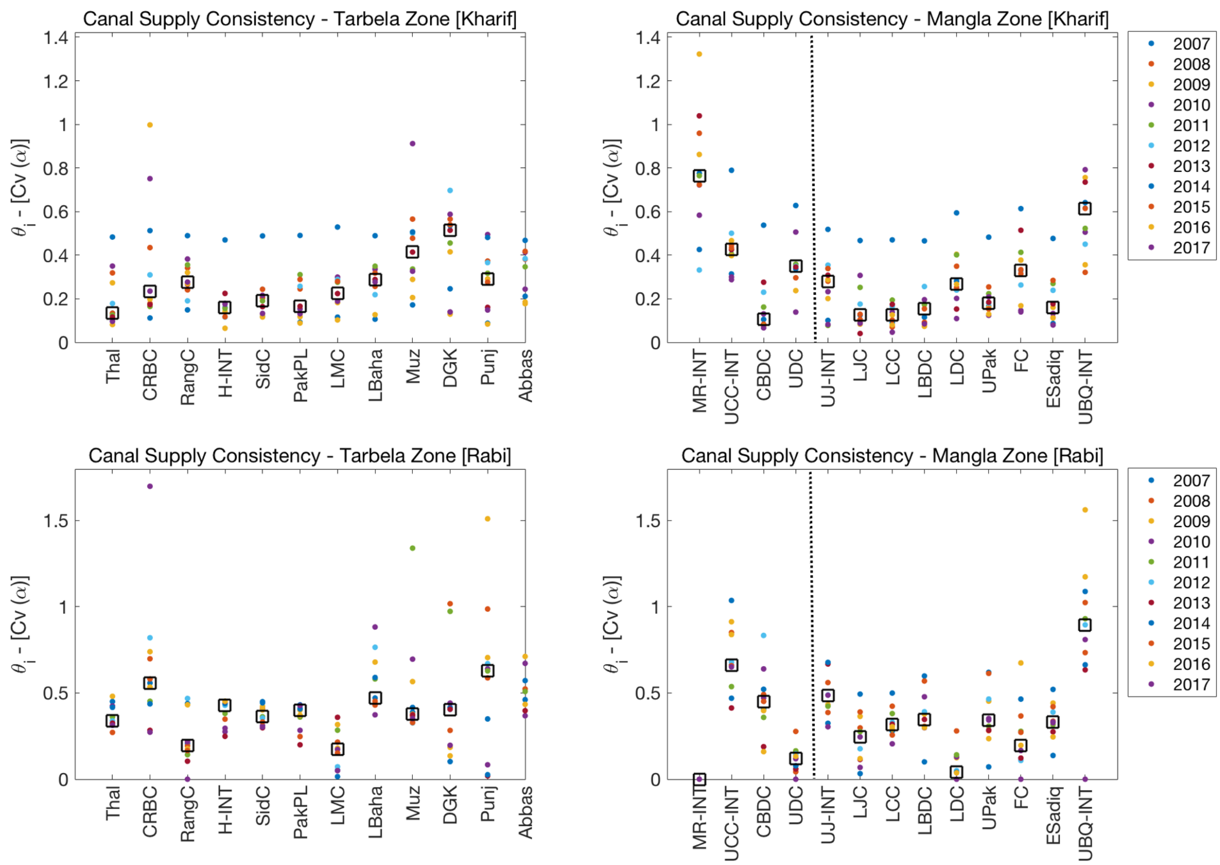

Fig. 4. Canal supply consistency (that measures intra-canal variability in delivery to entitlement ratios within a season) for Tarbela and Mangla zone canals. The canals are ordered on the x-axis left to right from upstream to downstream position in the two zones of the irrigation network. Dots represent data for a single year and median across 2007–2017 for each canal is shown as the black square marker.

work with.

In order to assess which canals may be subject to challenges of consistency, along with overall gross shortages of supply, we determined canal compliance (fraction of total entitlement volume to total delivered volume, regardless of timing of delivery). We computed inter-annual variability of compliance, X^i, and plotted it against mean canal consistency for the 2007–2017 period (Fig. 5).

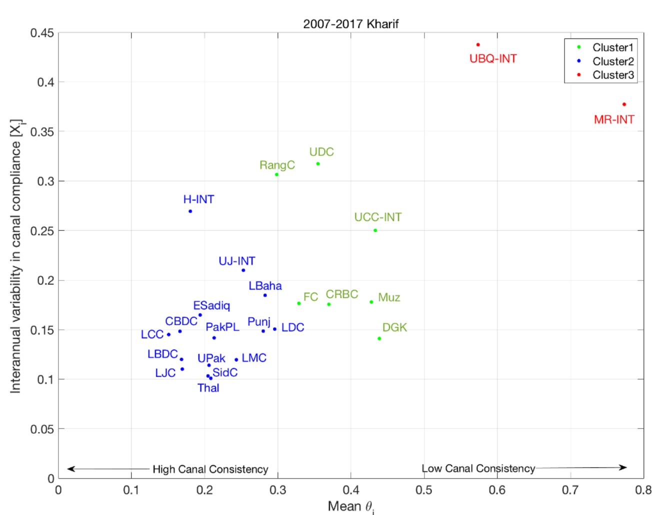

Fig. 5. Mean canal consistency and inter-annual variability in compliance (2007–2017) reveals three distinct clusters of canals. Plots such as these can be used to identify targets (canals) for further monitoring and evaluation and management intervention.

A set of three distinct clusters were identified with k-means clustering analysis in the X^i- θ^ispace. In the first case, there are two canals that exhibit high value of θ^i (they have low consistency as their deliveries do not match well with scheduled entitlements) and also high values of X^i (high interannual variability in compliance). These two canals, marked in red, are inter-link canals (the Marala-Ravi and the Upper Bahawal inter-link). The second cluster (marked in green) are canals with relatively improved consistency (lower value of θ^i) but also with high inter-annual variability in compliance. Interestingly, this second cluster includes canal commands dependent on the less reliable Marala barrage as well as those downstream on the Indus main stem in the drier and less productive Punjab Cotton-Wheat West zone. The third cluster (marked in blue) has comparatively the best attributes with low values of θ^i and X^i. These plots of consistency and compliance provide a relative comparison of performance across canal commands that have important implications for productivity.

4.3. Canal reliability

Reliability, ρ^i, for all the canals in most of the years was found to be below 1 (Fig. 6). The reliability in Kharif is higher than in Rabi for each canal, which may be associated with higher river inflows in the Kharif season. The reliability in Tarbela command canals is higher than in Mangla command canals, which may reflect in part the high volume and low coefficient of variation in annual Indus River inflows. The median reliability across all the canals ranges from 56% to 97% in Kharif and 32% to 96% in Rabi season. One influencing factor on reliability is position of the canals in the network. A slight trend of decreasing median reliability is evident from upstream to downstream canals in both zones (left to right on the x-axes), however there are

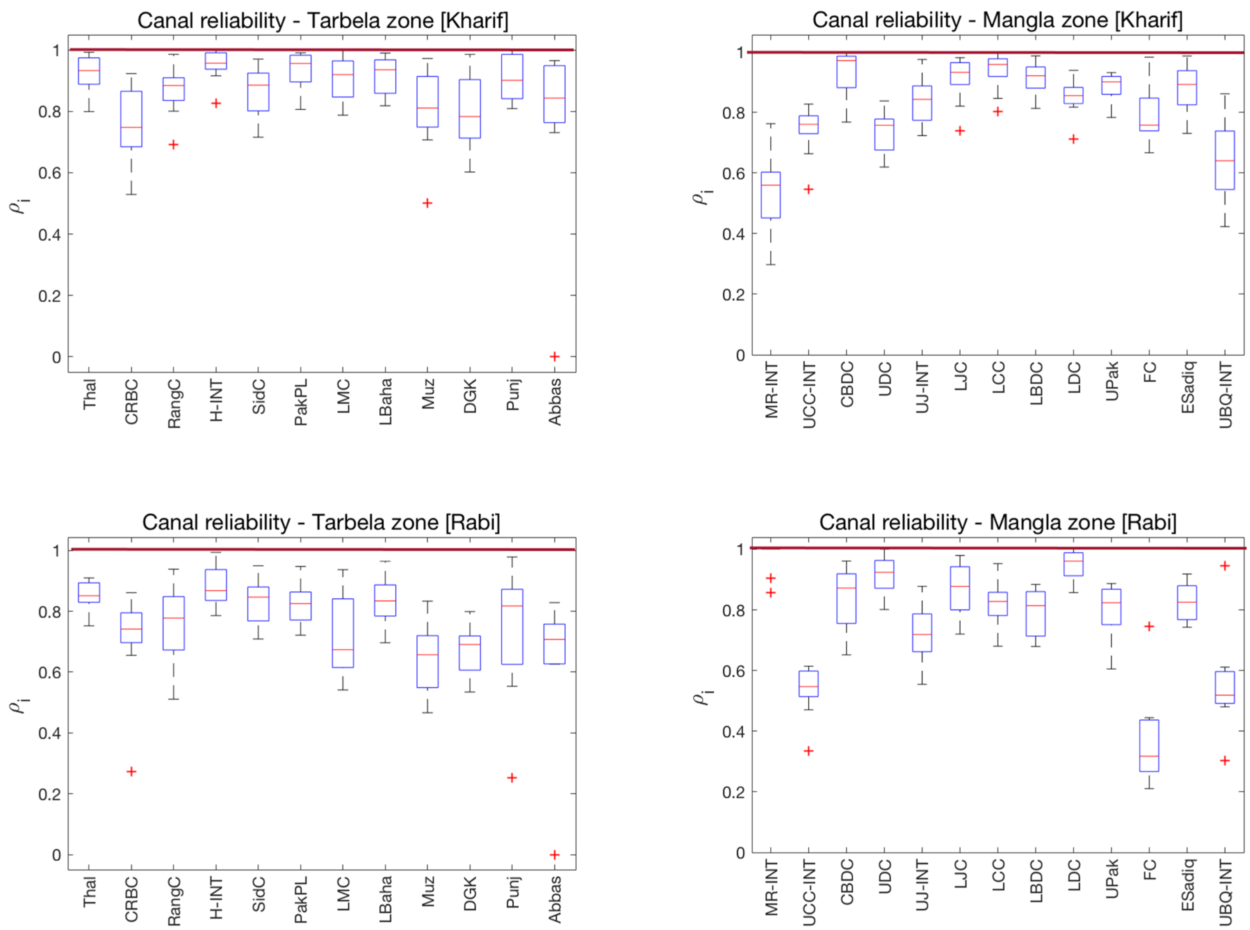

Fig. 6. Canal reliability ρ^i (likelihood of receiving full entitlement in an irrigation turn) for Tarbela and Mangla zone canals in Kharif and Rabi seasons.

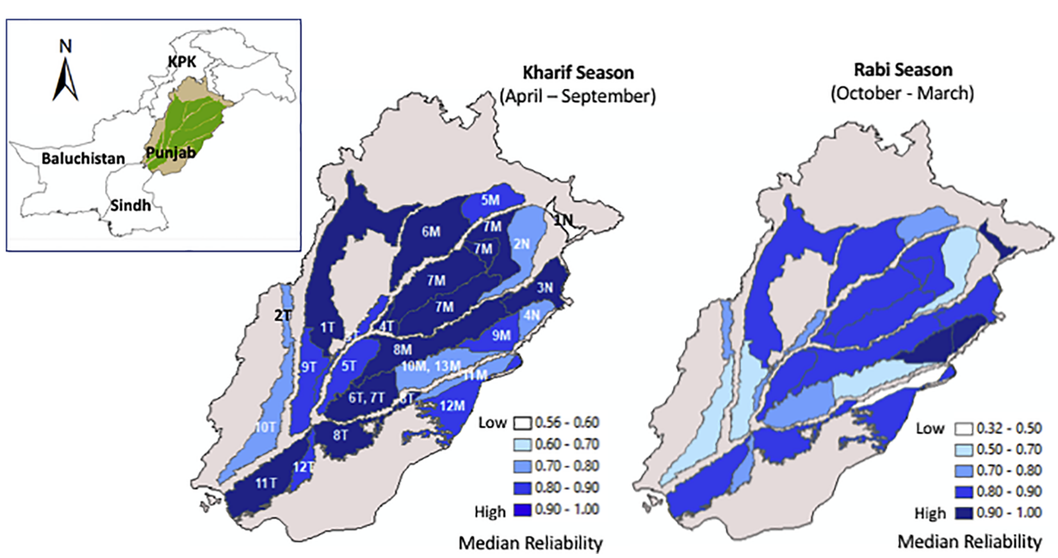

Fig. 7. Canal command areas in the Punjab province shaded with levels of median canal reliability in the 2007–2017 period. The regions are marked with labels given in Table 1. The inset figure shows a map of Pakistan with green area showing canal irrigated region in the Punjab province. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

some notable exceptions such as the Chashma Right Bank Canal (CRBC) in Tarbela zone (Figs. 6 and 7).

The lowest median reliability is observed for Fordwah Canal which is located downstream in the Mangla command in the Rabi season. If this is compared with data of 'unscheduled deliveries' shown in Fig. 1, Fordwah canal has the highest number of such deliveries, indicating that while this canal has low likelihood of receiving its entitlement on its scheduled turn (entitlement), it receives a high number of unscheduled deliveries. Therefore, in aggregate it receives its entitled water over the course of the season, but it is not delivered at the officially scheduled times. Given that this pattern is consistent from year to year, it points to the possibility that unscheduled deliveries are made to

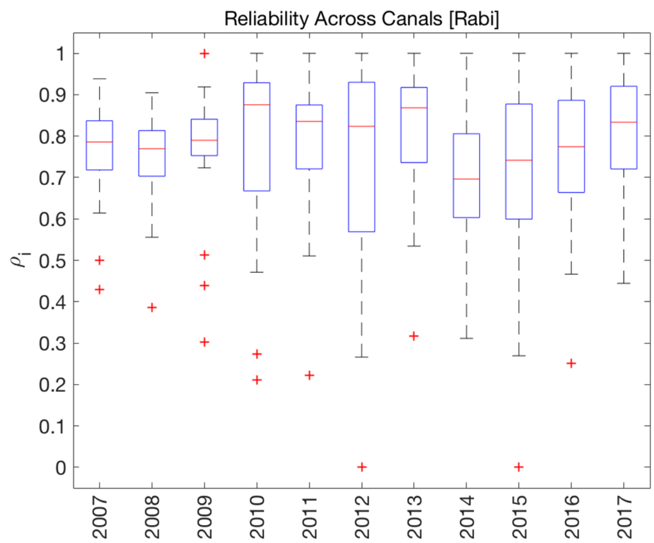

Fig. 8. Box plots of canal reliabilities distribution for each year in Rabi.

compensate for low reliability; as well as to the need for examining the process of how entitlements and schedules are set, and what if any procedures can be put in place to improve management and operations. These results also point to the critical issue of timing of deliveries, as timing of irrigation applications impacts yields. In many regions of Punjab, farmers have augmented surface supplies with pumped groundwater for irrigation [34], and recent studies show that the major drivers of groundwater use are the variability and uncertainty associated with surface water delivery [40].

Due to the lower reliability and comparatively higher variation in the Rabi season, we examined the annual trend of canal reliabilities in Rabi (Fig. 8). The annual trend shows increasing variability over time which is detrimental for productivity of the important wheat crop grown in the province during the Rabi season.

4.4. Interpreting patterns of consistency and reliability

Previous sections have introduced several factors that help explain differences in the improved metrics of consistency and reliability developed here. With only 12 canal commands served by the Indus and 13 by the Jhelum, a regression-based analysis is not possible to quantitatively assess the driving factors of consistency and reliability. However, Figs. 4, 6 and 7 show that trends in these measures are influenced by source (river inflows), reservoir storage, and network hierarchy (upstream versus downstream position). For example, canals linked to rivers that have no direct reservoir storage show greater variability. Second, there is a general decrease in consistency and reliability for canals from upstream to downstream locations, which indicates issues of equity as well as water delivery challenges over longer transit distances. This pattern is correlated with cropping patterns that have higher water requirements in upstream locations (Punjab Rice-Wheat and Punjab Sugarcane-Wheat); and cropping patterns that have lower water requirements (Punjab Cotton-Wheat) in downstream locations. Third, there are exceptions such as the comparatively higher consistency and reliability of the Central Bari Doab canal (CBDC), and the more downstream Panjnad canal and Eastern Sadiqia canals, which again raise questions of equity as well as pragmatic aspects of water delivery.

We explored the potential impact of canal command size as an additional factor that influences these patterns, with the expectation that larger commands would have more reliable supplies. Fig. 9 shows median θ^i and ρ^i plotted with canal command area, and a clear trend of increasing consistency and reliability with command area is evident in the Mangla zone while a weaker positive trend is evident in the Tarbela zone. Thus, canals serving large amounts of land have comparatively better consistency and reliability as compared to canals serving smaller areas, which might be attributed to larger and more readily fulfilled claims on the system.

4.5. System equity and network reliability

For the final analytical synthesis of system behavior, we map system equity (mean ε_k) and network reliability (mean ρ^i) for each season (Fig. 10). This type of mapping helps assess system performance, and visualize where course correction is needed. In an ideal case, a system's trajectory should tend towards the green dot in Fig. 10, indicating the utopia point that has perfect equity and perfect network reliability.

The results in Fig. 10 show that there is no clear trajectory of the system reliability and equity measures, which instead exhibit an oscillating trend during the 2007–2017 period. Also, there is a worsening of the system behavior in the winter (Rabi) months as compared to the summer, and system equity is lower in Rabi on average by 26% as compared to Kharif. It is apparent from these results that crops grown in the Rabi season, including the major staple crop of wheat in the region, are likely to be subject to adverse impacts [41]. Furthermore, the overall production in the province is likely to show significant variation in crop production due to the low levels of equity. Variations in network equity require additional analysis of entitlement and delivery relationships across canal commands. In a recent analysis of 2013–2016 wheat yield data for Punjab, we have found that there is significant variation in yield and water used by farmers across canal commands [42]. In future studies, we will use the socio-hydrologic framework and results of this work to evaluate hypotheses about water security, crop production, and food security [43].

5. Summary

The irrigation system of the Indus has been studied from a variety of perspectives, but this socio-hydrologic assessment is the first to examine the reliability and equity of water deliveries to twenty-five major canals across the province of Punjab in Pakistan over the period of a decade. Our analysis reveals that the vast surface irrigation network in the Punjab exhibits significant variation in reliability measures across seasons in these canals. While variations between the head and tail areas of smaller channels, such as distributaries and watercourses, are well-documented, this analysis reveals variations across major canals as well. Median canal reliability ranged widely, from 56 to 97% in Kharif and from 32% to 96% in Rabi, which we interpret in part as a function of lower mean discharge in Rabi season inflows. Interestingly, canals in the eastern part of the province served by the Jhelum exhibit higher consistency in supply than those served in downstream reaches of the larger Indus river, which raises issues of system operations and equity. We note that downstream canal commands have cropping patterns adapted to lower and more variable water supply. We also find that for some canals in both zones there is a consistent mismatch between entitlement times and deliveries. These variations across space and time can have real impact on the productivity of agriculture where timing of irrigation is key, and by extension on the socio-economic conditions of the large population that relies on this system. Recent studies with flow sampling at 10-minute intervals at selected distributaries (branching from main canals) in Punjab have shown that 10-daily reported data can mask significant variations at higher time resolution[13,44]. In future work, we plan to show how the network-level and canal-level attributes relate to performance attributes at the finer watercourse scale.

At the network level, we find that the system equity is overall worse in Rabi season on average by 26% as compared to Kharif, which may be explained in part but not wholly by lower Rabi inflows. It is a concern that network equity does not show any consistent positive trend over time. Rather we observe 'noise' in the system and find no indication of

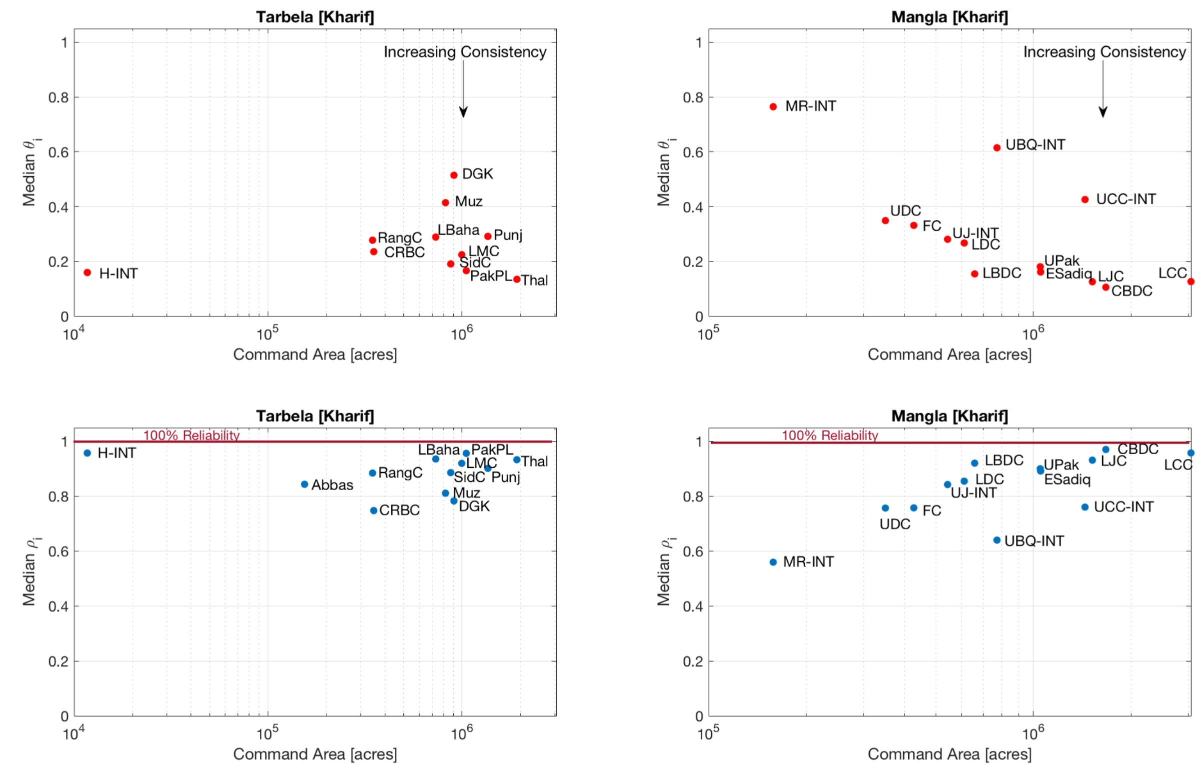

Fig. 9. Median canal consistency (top row) and reliability (bottom row) versus canal command area in Kharif season. The consistency and reliability show an increasing trend with area in the Mangla zone. In the Tarbela zone, consistency shows no apparent trend and reliability shows a mildly increasing trend with canal command area.

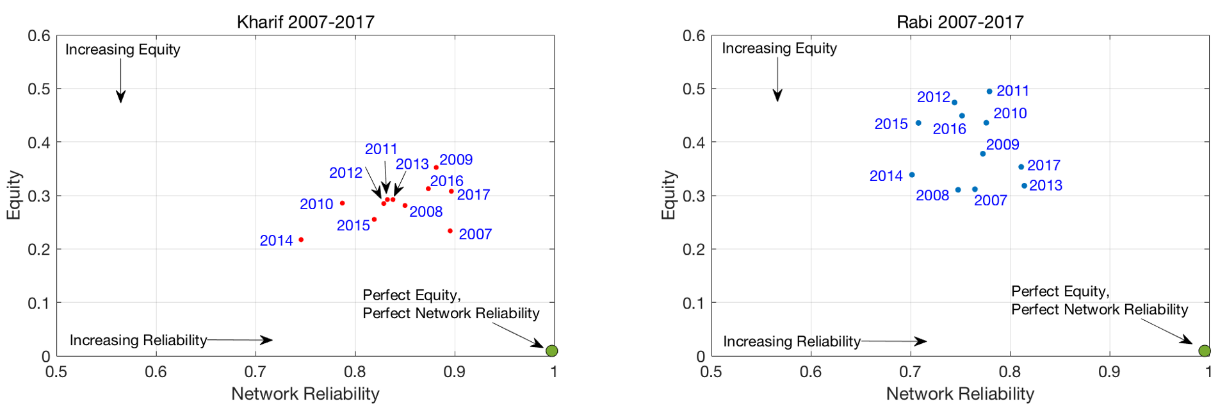

Fig. 10. The network reliability (mean ρ^i) and system equity show oscillatory behavior. Performance in Rabi (winter season) along both equity and reliability dimensions is worse as compared to Kharif (summer season).

improvement in water security as defined in this work. The results show that overall system equity and reliability are moving in a wavering rather than an improving trajectory.

At the same time, these results indicate that there is significant theoretical potential to positively affect performance and water security through interventions in water delivery forecasting and management. The performance measures used in this work are based on a comparison of entitlements and deliveries data. Any improvement in the entitlements allocation and scheduling alone that accounts for geographical and technological factors for each canal can lead to better potential performance outcomes. For certain canals, the reported data shows that entitlements are not duly met, year after year. In such cases, either the entitlements should be revised or technical interventions in the supply network should be undertaken to ensure that deliveries closely follow seasonal entitlements for each canal.

In addition to contributing a new socio-hydrological framework for analyzing water security, this paper defined quantitative metrics of equity and reliability in a canal irrigation network. While there has been significant attention devoted separately to issues of equity [29] and of reliability, the two have seldom been considered jointly in quantitative studies. Here, a set of metrics and graphic representations have been formulated to better understand system behavior, identify opportunities for management interventions, and direct the system trajectory towards desired levels of performance. While the framework is applied to study the irrigation system in Punjab, Pakistan, the approach and metrics can be used to study systems in other regions, in which comparative analysis can be performed.

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