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Equity in a tertiary canal of the Indus Basin Irrigation System (IBIS)

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ABSTRACT

This paper examines the fairness in distribution of water in a tertiary canal within the Indus Basin Irrigation System. Two methodologies are proposed: canal rating equations, and outlet discharge equations. The methodology is applied to a tertiary canal located in the Punjab, Province of Pakistan. Fairness/equity is expressed quantitatively using the Gini index. There is a difference in the estimated discharge depending on the methodology employed, however as we move along the canal the water allowance does not vary significantly with the distance along the canal. Hence for this particular canal the head-middle-tail inequity often reported and generalized in the literature is not observed. The advantage of a quantitative measure of inequity such as the Gini is exemplified by comparing the Gini with that at the secondary canal and also against itself if the tertiary canal could be operated "as designed". We introduce two new concepts: systematic and operational inequity. Provided the costs of data acquisition can be reduced this technology has the potential to be scaled up and included in future development investments in large scale irrigation systems. Further work exploring the impact of information on stakeholders needs to be undertaken.

1. Introduction

The vast Indus Basin Irrigation System (IBIS) in Pakistan often cited as the world's largest contiguous irrigation system e.g. Basharat et al. (2014) is essentially a run-of-the-river system which can be characterized as a gravity based system with a modest storage capacity. The IBIS follows a fairly standard layout of a primary canal receiving water at a barrage constructed across the River Indus or one of it's tributaries. This primary canal in-turn divides into secondary canals. Each secondary canal in turn divides into any number of tertiary canals. Primary canals typically receive water directly from a river and invariably the discharge in these canals fluctuate over time. The primary and secondary canals are operated continuously (with the exception of an annual maintenance period in January). Tertiary canals are operated in a more binary mode using a canal roster where, during any given interval (typically weekly), some tertiary canals are operated and others remain closed.

The final piece of critical infrastructure is the canal outlet or turnout. A tertiary canal will have any number of outlets. Canal outlets are typically designed hydraulically as open flumes or orifices. Each canal outlet has a designated irrigated area and the rated or design discharge of an outlet is estimated using this designated irrigated area and the capacity per unit irrigated area of the tertiary canal – known colloquially as the *water allowance*. Water flows from the tertiary canal through these outlets into field channels/watercourses. When a tertiary canal is operated it is preferable to maintain a flow at or near capacity. This ensures that

- the water in the canal is at the correct elevation to command adjacent fields as water flows onto the fields by gravity;
- the turnouts or outlets along a tertiary canal release discharges into field channels roughly equal to the rated discharge of the outlet to minimize inequity within/along the distributary; and,
- the velocity in the tertiary canal is approximately equal to the designed non-silting, non-scouring velocity to avoid silting and/or scouring.

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Canal outlets are particularly critical because outlets control the discharge into watercourses by virtue of their size and hydraulic characteristics (orifice or flumes). Outlet dimensions remain fixed other than any changes made for purposes of maintenance, hence as opposed to sluice gates between a primary and secondary canal or between a secondary and tertiary canal which are adjusted to manage flows (active management), the outlet that controls flow between a tertiary canal and a field channel does not have any gates or any adjustment (passive management). Canal outlets are also critical because beyond this point the flow is managed sequentially whereas above the canal outlet flow is managed simultaneously. Whereas several secondary canals may flow simultaneously, several tertiary canals may flow simultaneously and several outlets may flow simultaneously, downstream of an outlet farmers receive water sequentially i.e. two farmers on a given field channel will not receive water simultaneously rather they will receive water in sequence according to a fixed weekly schedule.

It is widely documented in the literature that Pakistan's IBIS characterized above neither has the capacity nor the water resource to irrigate the entire area of 17.5 Mha. Rather this irrigation system was designed to irrigate a fraction of the total area at any given time. The deficit-by-design of the Indus Basin Irrigation System is widely reported e.g. Seckler et al. (1988), Hussain et al. (2011), Khepar et al. (2000) and is one of the reasons that substantial areas of land remain fallow within the irrigation system during any given season. Seckler et al. (1988) have stated on average a farmer will irrigate 1/3 of the culturable command area (CCA) four times per season also supported by Hussain et al. (2011) who state that surface-water supplies can fulfil only 30% of the irrigation demand. The Indus Basin Irrigation system is managed by a *warabandi* system. A literal translation of *warabandi* is "fixed turns" as described by Sharma and Oad (1990). This is only one facet of the *warabandi* with the fixed turn in reference to the typically once-a-week turn of a farmer to receive water as a mechanism to use water sequentially from a shared watercourse. Malhotra (1982) makes the case that the *warabandi* is in fact a comprehensive management system for the specific nature of the IBIS. A particular feature as highlighted above is that the irrigation system was intentionally designed to deliver only a fraction of the water needed to fulfil crop evapotranspiration. Hence the system has also been described as a "supply-based-system" rather than a "demand-based-system" to articulate that the system simply supplies what water is available rather than responding to any demand placed by users or crop requirements.

As a result with few notable exceptions, the Indus Basin Irrigation System has been designed and is managed to distribute or ration this inadequate water in some fair or equitable way (Rinaudo, 2002). This fact is central to the *warabandi* system of management, Bhutta and Velde (1992). A *warabandi* irrigation system is designed and operated such that each user receives an identical, albeit inadequate volume of water per unit area. Any deficits (or in rare occasions surpluses) of water are shared equally amongst all users and hence the principle of fairness or equity remains valid. Equity in the context of income distribution is an extensively studied subject in economics and econometrics. Young (1994) has described equity in broad economic terms as seeking to redress social imbalances but it resists simple formulation. Sampath (1988) supports this appeal of equity and that in a qualitative sense it appeals to a sense of fairness. However Sampath (1988) notes that equity beguiles the complexity of defining and measuring it. Mustafa (2002) adds a perspective to equity as one that "*. . ..implies procedural fairness, transparency. . ..*" although such a qualitative description is again appealing, it would belie defining a quantitative measure. Even in the much narrower context of water management, Molden and Gates (1990) pointed out how difficult it is to define a "fair share" a view also held by Maskey et al. (1994). Despite the difficulty of defining and measuring equity (or inequity), improving equity of water management often remains a stated aim of significant development investments. For example, the World Bank funded project PK Sindh Water Sector Improvement Project Phase-I has the stated objective "*The objective of the additional financing for the First Phase of Sindh Water Sector Improvement Project for Pakistan is to improve the efficiency and effectiveness of irrigation water distribution . . . .particularly with respect to measures of reliability, equity and user satisfaction.*" World Bank (2016). Similarly the Asian Development Bank (2015) states "*The Comprehensive Development Strategy* (*CDS*) 2010–2017 *in Khyber Pakhtunkhwa Pakistan* (*KPP*) *highlighted key issues in the Irrigated agriculture and water resources* (*IAWR*) *sector* . . .(ii) *inequitable water supply distribution and low cost recovery*, *which has resulted in deferred maintenance*;. . .". The importance placed on equity is also emphasized in the (draft) Pakistan National Water Policy—Government of Pakistan (2012). Mustafa (2002) in interviews with officials of the Punjab Irrigation Department determined that almost all identified "*. . ..equitable distribution of water to water users. . . . . ..as their main organizational mission*", and goes on further to state "*. . ..water related officials in the country consider it imperative to address issues of equity*."

With the caveat that there is no simple definition of equity or fair share even in the narrower context of water management and acknowledging the importance of equity in the IBIS, Anwar and Haq (2013) proposed that in a *warabandi* managed irrigation system the cumulative volume per unit area could be used as the variable of interest and the Gini or Theil index can be used as a summary statistic of the cumulative volume per unit area to measure equity. Anwar and Haq (2013) demonstrated this by applying this philosophy to a case of a secondary canal i.e. between tertiary canals in south-east Punjab, Pakistan and also go on to suggest from anecdotal evidence that there may be more pronounced inequity within a tertiary canal i.e. between canal outlets rather than within the secondary canal. The difficulty of measuring flows at canal outlet levels is widely documented especially in the literature on volumetric water charging e.g. Cornish et al. (2004), Laycock (2007) and Molle and Berkoff (2007). Vos and Vincent (2011) citing Wade (1990), Sampath (1992) Plusquellec et al. (1994), Horst (1999) identify *the distribution of exact volumes is likely to be challenging in large-scale systems with open canals and gated systems under operator control*, *because of vulnerability to breakdown*, *constantly fluctuating flow targets*, *unsteady flow and tampering, especially when the canal supply is irregular*. Soler et al. (2015) also identified the control of water distribution amongst canal outlets' as one of the more difficult problems in water management because of the difficulty of measuring flows at this level and the spatial and temporal variability and address the issue of unsteady state flow in particular.

In the context of the 17.5 Mha irrigated area of the IBIS with each outlet on average designed to irrigate approximately 150 ha there are more than 115,000 outlets in Pakistan. To cover this entire spatial extent and just one measurement per day (to cover temporal variation) would require over 40 million measurements per annum! This data estimate does not include other canal and/or outlet parameters that need to be recorded periodically e.g. quarterly, half-yearly or yearly. It is therefore unsurprising that no serious attempt at measuring outlet discharge on any regular basis within the IBIS has been made. Rather the discharge at the head of a canal (typically normalized by canal capacity and referred to as delivery performance ratio) and/or the depth of flow at the tail-end of a canal are used as measures of performance management.

In this research paper we expand on the work of Anwar and Haq (2013) and explore estimating equity at a tertiary-level (distributary) canal. We develop and compare two alternative techniques to evaluate equity in a tertiary canal, the first technique uses estimates of discharge along the tertiary canal and the second uses estimates of discharge through the tertiary canal outlets. We also examine whether the measures of performance management are explanatory variables of this measure of equity. This paper is limited to equity and does not discuss other equally important performance indicators such as reliability or adequacy. This paper does not describe the experience and techniques of automating data acquisition, transmission, archiving and processing to overcome some of the difficulties of measuring flows at this level of a large irrigation system, nor does this describe the role of irrigation institutions in information systems. These are the subject of ongoing research by the authors.

2. Materials and methods

The study area is located in the Punjab province of Pakistan and is shown in Fig. 1. This area is predominantly a cotton-wheat growing area with cotton grown in the summer (*Kharif*) season and wheat in the winter (*Rabi*) season. The primary canal – Eastern Sadiqia Main Canal receives water at the Sulemanki Barrage constructed across the River Sutlej. This Eastern Sadiqia Main Canal in-turn divides into two secondary canals – Hakra Branch Canal and Maliki Branch Canal. The Hakra Branch Canal is 87,148 m in length, has a capacity in the head reach of 82.03 $m^3 s^{-1}$ and a designated irrigated area of 221,543 ha (0.37 $Ls^{-1} ha^{-1}$). The canal head regulator of Hakra Branch Canal is located at 29.56°N, 73. 20°E. The secondary Hakra Branch Canal in turn has 17 tertiary canals listed in Table 1. The tertiary canal 5R offtakes at a running distance of 43,800 m along Hakra Branch Canal i.e. the tertiary canal 5R offtakes at approximately the mid-length of the secondary canal.

Table 2 reports the key characteristics of the secondary Hakra Branch Canal and the tertiary canal 5R which are the focus of this study. The capacity of tertiary canal 5R is 1.03 $m^3 s^{-1}$ and if the entire designated irrigated area of 3713 ha were to be irrigated (i.e. farmers did not leave any land fallow) this translates to 2.37 mm/day. In summer the crop (cotton) potential evapotranspi-

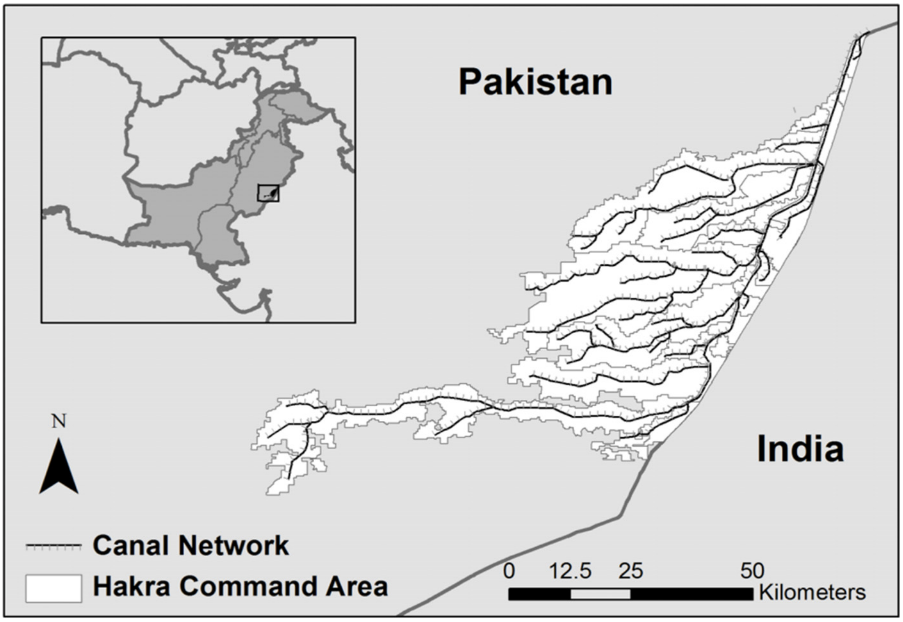


Fig. 1. Study Area.

Table 1
Tertiary canals from secondary canal Hakra Branch Canal.

#	Offtake Reduced Distance RD (m)	Bank	Tertiary Canal Name (long form and short form)		Capacity at head ($m^3 s^{-1}$)	Length (m)	Designated irrigated area (ha)	Capacity per unit area	
								($Ls^{-1} ha^{-1}$)	mm/day
1	10,058	Left	Baku Shah Distributary	BS	0.17	835	609	0.28	2.41
2	18,654	Right	Sundar Distributary	1R	0.54	3703	2009	0.27	2.31
3	22,662	Right	Dunga Bunga Distributary	2R	0.62	10,278	2147	0.29	2.51
4	25,527	Left	Mubarik Distributary	1L	2.35	23,698	6917	0.34	2.94
5	27,356	Right	Khatan Distributary	3R	10.00	49,493	29,442	0.34	2.93
6	27,356	Right	Haroonabad Distributary	4R	6.40	34,153	17,585	0.36	3.14
7	43,800	Right	Bhagsen Distributary	5R	1.02	10,429	3713	0.27	2.37
8	50,231	Right	Mamun Distributary	6R	15.46	45,220	41,204	0.38	3.24
9	50,231	Left	Mianwala Distributary	2L	0.54	6534	1769	0.30	2.63
10	56,906	Right	Khichiwala Distributary	7R	7.73	40,392	21,794	0.35	3.06
11	59,659	Left	Malkir Distributary	3L	0.28	3871	703	0.40	3.48
12	68,580	Left	Kamrani Distributary	4L	0.25	3229	682	0.37	3.23
13	69,875	Right	Josar Distributary	8R	0.68	11,799	2573	0.26	2.28
14	77,489	Right	Sardrewala Distributary	9R	5.97	35,611	19,909	0.30	2.59
15	86,966	Left	Hakra Left Distributary	HL	0.65	7152	2418	0.27	2.33
16	86,966	Centre	Flood Channel Distributary	FC	2.07	21,080	6684	0.31	2.67
17	86,966	Right	Hakra Right Distributary	HR	14.44	75,545	42,893	0.34	2.91
Sum					69.18		203,052		
Average								0.32	2.77

Table 2
Key characteristics of secondary canal Hakra Branch Canal and tertiary canal 5R.

Canal name (long form)	Hakra Branch Canal	Bhagsen Distributary
Canal name (short form)	–	5R
Flow type	Perennial	Perennial
Capacity per unit area	0.37 $\mathrm{Ls^{-1}\,ha^{-1}}$ (3.20 $\mathrm{mm\,day^{-1}}$)	0.27 $\mathrm{Ls^{-1}\,ha^{-1}}$ (2.37 $\mathrm{mm\,day^{-1}}$)
Capacity at head	82.03 $\mathrm{m^3\,s^{-1}}$	1.03 $\mathrm{m^3\,s^{-1}}$
Designed depth of flow at head	2.31 m	0.83 m
Designed depth of flow at tail	1.83 m	0.31 m
Designated irrigated area	221,543 ha	3713 ha
Length	87,148 m	10,431 m
Outlets directly from this canal	88	26
Parent canal	Eastern Sadiqia Canal	Hakra Branch Canal
Number of child canals	17	0
Location of head regulator (m)	74,676 m	43,800 m

Table 3
Gauges and outlets along tertiary canal 5R.

Gauge #	Gauge RD (m)	Rating Eq. coefficient ($\mathrm{m^{4/3}\,s^{-1}}$)	Outlet #	Outlet RD (m)	Designated irrigated area (ha)	Outlet rated discharge (L/s)
0						
1	908	1.0362	1	898L	169.23	43
			2	902L	215.38	56
			3	924L	126.72	32
2	1777	1.4466	4	1774L	203.24	51
			5	1805R	152.23	39
3	2783	1.4282	6	2781L	182.19	46
4	3451	1.1840	7	3449R	106.48	27
5	3794	1.0855	8	3796R	129.55	33
		1.0855	9	3797L	123.48	31
6	4491	1.2148	10	4488L	163.56	41
			11	4492L	188.26	47
7	4829	0.9788	13	4824R	127.13	33
			12	4828L	158.70	40
8	5243	0.8372	14	5240L	180.97	46
9	5868	0.9603	16	5863R	35.63	10
			15	5869R	141.70	35
10	6038	0.9808	17	6037L	202.43	57
11	7137	1.0485	18	7141R	59.51	15
12	7607	1.1963	19	7425R	123.08	37
13	8207	1.0465	20	8215R	117.41	29
14	8337	1.0280	21	8343L	108.91	29
15	8894	1.3748	22	8891R	115.79	29
16	8918	1.2558	23	8915L	174.90	29
17	10434	0.8105	24	10448TR	162.75	51
			25	10448TC	144.53	36
			26	10448TL	158.30	40
Total					3772.06	962

ration in this irrigation command area exceeds 5 mm/day (author's measurements). In practice the system does not run continuously at capacity and the entire 2.37 mm/day would not necessarily reach the root zone of the crop due to inefficiencies. This emphasizes the deficit-by-design nature of this canal system which is typical of the Indus Basin Irrigation System, and explains why water management and equitable distribution of water are synonymous in the *warabandi* system of canal management.

At the head of each of the tertiary canals of Hakra Branch Canal a stilling well was constructed. This was instrumented with an ultrasonic range finder connected to a datalogger. Measurements were recorded every 10 min. There are 26 canal outlets on the tertiary canal 5R as shown in Table 3. At each outlet a gauge was installed to measure the depth of flow in the tertiary canal. These gauges also consisted of an ultrasonic range finder connected to a data logger but installed on a gantry above the canal rather than in a stilling well. Measurements were recorded every 15 min. Where outlets are located in close proximity (clusters) a single gauge was installed for each outlet cluster. Hence there are 17 gauges to measure the depth of flow in the tertiary canal adjacent to 26 outlets as shown in Table 3. Gauge 0 is not associated with any outlet and measures the depth of flow at the head of the tertiary canal. In total 34 gauges were installed for this research. The typical cost of each gauge with instrumentation and sensors is approximately USD 3000 (2014 prices). The range finders measure the range to the water surface from which with additional survey data the depth of flow can be estimated.

Table 4
Rating curve coefficient for tertiary canal gauges.

Tertiary Canal	Date and time of calibration	Rating Eq. coefficient ($m^{4/3}\,s^{-1}$)
Baku Shah Distributary	Feb/1/2015 12:34	1.920
	Jun/11/2015 11:28	2.170
Sundar Distributary	Mar/5/2015 11:23	7.610
	Mar/12/2015 9:51	7.610
	Jun/11/2015 11:06	7.630
Dunga Bunga Distributary	Mar/7/2015 11:37	8.160
	Jun/11/2015 11:14	7.070
Mubarik Distributary	Feb/9/2015 10:08	13.010
	Jun/11/2015 11:03	10.210
Haroonabad Distributary	Feb/9/2015 12:19	45.610
	Jun/11/2015 11:19	36.880
Khatan Distributary	Feb/9/2015 11:43	64.320
	May/20/2015 8:37	64.320
	Jun/11/2015 11:16	45.980
Bhagsen Distributary	Mar/14/2015 12:23	5.500
	Jun/11/2015 11:20	6.490
Mamun Distributary	Feb/27/2015 12:25	34.180
	Jun/11/2015 11:21	36.860
Mianwala Distributary	Feb/27/2015 11:28	7.360
	Jun/11/2015 11:13	7.910
Khichiwala Distributary	Feb/25/2015 12:28	24.400
	Jun/11/2015 11:23	20.200
Malkir Distributary	Feb/25/2015 11:40	5.800
	Jun/11/2015 11:15	4.910
Kamrani Distributary	Mar/2/2015 11:45	10.000
	Jun/11/2015 11:17	8.270
Josar Distributary	Mar/2/2015 12:30	8.600
	Jun/11/2015 11:23	9.500
Sardrewala Distributary	Mar/4/2015 12:32	16.020
	Jun/11/2015 11:25	19.070
Flood Channel Distributary	Feb/9/2015 12:36	9.010
	Jun/11/2015 11:26	11.920
Hakra Left Distributary	Feb/9/2015 12:38	10.530
	Jun/24/2015 14:25	10.720
Hakra Right Distributary	Feb/9/2015 12:41	33.770
	Jun/11/2015 11:27	33.650

2.1. *Estimating discharge along the tertiary canal*

Gauge readings were corrected for any zero error and converted to depth of flow. A semi-empirical rating curve for each gauge was developed assuming a wide rectangular channel and uniform flow conditions. For a rectangular channel from the continuity equation, Manning's equation and applying L'Hopital's rule for wide rectangular channels, discharge can be estimated from

$$Q = \left(\frac{BS^{\frac{1}{2}}}{n}\right) y^{\frac{5}{3}} \qquad (1)$$

Where Q = discharge; B = width; S = bed slope; n = Manning's roughness; and y = depth of flow. Alternatively the rating equation can be expressed as a power-law equation of the form

$$Q = Ky^{\frac{5}{3}} \qquad (2)$$

Where K = rating equation coefficient ($m^{4/3}\,s^{-1}$). For the purposes of this work the rating equation coefficient was determined empirically from depth of flow and discharge measurements. Discharge was measured using electromagnetic current meters and/or an Acoustic Doppler Current Profiler (ADCP). The rating equation coefficient for each of the 34 gauges is reported in Tables 3 and 4. For each measured range, discharge was estimated using (2). From the average daily discharge the volume per unit area flow past any given gauge was estimated. Areas were calculated based on the designated irrigated area downstream of the gauge as shown in Tables 1 and 3. This technique of using a semi-empirical form of a wide rectangular channel is used universally throughout the IBIS. Calibration of the semi-empirical equation is simply an estimation of the rating equation coefficient and the date and time of calibration shown in Table 4 illustrates that with one or two exceptions the estimated rating equation coefficient does not vary significantly with time.

2.2. *Estimating discharge through tertiary canal outlets*

The discharge through canal outlets is estimated using flume or orifice flow equations given by

$$\text{for free flowing fume flow} \quad q_f = C_{df} BH^{3/2} \qquad (3)$$

$$\text{for free flowing orifice flow} \quad q_o = C_{do} BYH^{1/2} \qquad (4)$$

Where q_f = discharge under flume flow conditions; C_{df} = discharge coefficient for flume flow conditions; B = width of orifice or flume; H = head over crest; q_o = discharge under office flow conditions;

C_{do} = discharge coefficient for orifice flow conditions; Y = height of orifice. Although canal outlets are designed as either flumes or orifices, in practice as the canal water level fluctuates if the water level drops below the soffit of the orifice it behaves hydraulically as a flume. Similarly most flumes will have some form of a covering often to allow construction of canal inspection roads. If the water level in the canal increases sufficiently then the flume will behave hydraulically as an orifice. For the purposes of estimating discharge through an outlet we use the minimum of the discharge predicted by the orifice and flume equations on the basis that the hydraulic conditions that limit the flow will prevail. Estimating the discharge through the outlets is further complicated because in most of the outlets the outlet is not located directly on the canal. Rather a pipe connects the canal to an outlet stilling well which in turn is connected to the outlet and in some cases there are significant head losses in the connecting pipe and stilling well. Strictly speaking head losses in a pipe are the summation of entry, exit and friction losses and has the functional form.

$$h_l = f\left(q^2\right) \tag{5}$$

Where h_l = head loss; q = discharge through the pipe. When this equation is combined with the outlet discharge equation(s) the resulting equation is no longer explicit and has to be solved through iteration. To avoid this we use a simpler regression between depth of flow in the canal and depth of flow in the outlet stilling well referenced to the outlet crest/sill level. We force the intercept of this linear equation to zero on the understanding that if the depth of flow in the canal above the outlet sill level is zero then it should also be zero in the outlet stilling well. Yet another complication with estimating outlet discharges is that some of the outlets are perpetually or intermittently drowned either because of accumulation of silt in the field channels or because a particular farmer needs to raise the water level in order for the water to flow on to his/her field which may be at a comparatively higher elevation with respectt to level of water in the watercourse. The flume and orifice discharge equations are invalid for drowned flow and therefore do not predict the discharge through the outlet under these conditions. To check the estimates of outlet discharge using (3) and (4) for a sample of outlets the discharge downstream of the outlet in the field channel was measured using an electromagnetic flowmeter.

2.3. Estimating equity

From either set of these calculated discharges (discharge along the tertiary canal or discharge through canal outlets) we summarize equity in the canal during any given *warabandi* week using the Gini index given by

$$G = \frac{1}{2N^2\bar{d}}\sum_{i=1}^{N}\sum_{j=1}^{N}|d_i - d_j| \tag{6}$$

Where G = Gini index; d_i = volume per unit area received by the i^{th} user; d_j = volume per unit area received by the j^{th} user; i and j are indices 1. . ..N representing any user; $\bar{d}$ = average volume per unit area; N = total number of users. The Gini is the sum over all users of the absolute difference of the average volume per unit area received by one user and all other users. This summation is divided (scaled) by the product of the square of the size of the population and the average volume of per unit area This scaling ensures the Gini ranges from 0 to 1, with 1 indicating perfect inequity (all water received by a single user) and 0 indicates perfect equity (all users receiving the same volume of water per irrigated area). The cumulative Gini is estimated from the volume per unit area delivered to each user from the beginning of the season up to and including a given *warabandi* week and is defined mathematically as

$$G_T = \frac{1}{2N^2\overline{D_T}}\sum_{i=1}^{N}\sum_{j=1}^{N}|D_{i,T} - D_{j,T}| \tag{7}$$

Where G_T = cumulative Gini up to and including *warabandi* week T (inclusive); $\bar{D}_T$ = average volume per unit area up to *warabandi* week T (inclusive); $D_{i,T}$ = volume per unit area received by the i^{th} user from the beginning of the season up to *warabandi* week T (inclusive); $D_{j,T}$ = volume per unit area received by the i^{th} user from the beginning of the season up to *warabandi* week T (inclusive) and

$$D_{i,T} = \sum_{t=1}^{T} d_{i,t}\,(\forall i = 1\ldots N,\,) \tag{8}$$

Where $D_{i,T}$ = cumulative volume per unit area received by the i^{th} user from the beginning of the season up to *warabandi* week T (inclusive). The results are reported aggregated over a week to correspond to the *warabandi* week for the summer (*Kharif* 2015) season 11th April 2015–9th October 2015 (26 weeks). *Warabandi* weeks start on the Saturday and end on the Friday of each week.

3. Results and discussion

3.1. Estimating equity using discharge along the tertiary canal

Fig. 2 presents the volume (per unit area) delivered during *Kharif* 2015 week 1 (11 April 2015–17 April 2015) against the length of the canal (running distance). Fig. 2 also shows the irrigated area which as expected decreases along the length of the canal. The objective of water rationing through the *warabandi* system of management is to supply a constant volume per unit area along the canal. The linear regression line in Fig. 2 shows that this objective is largely achieved for week 1. On average 12.6 mm of water was supplied during week 1 (1.8 mm/day) with the exception of farmers at the very tail-end of the canal who receive only 5.5 mm during this week. The slope of a linear regression line in Fig. 2 is 1×10^{-7} suggesting that for a farmer further along the canal by 1000 m will receive just 0.1 mm more water. Fig. 3 is a box plot that shows the volume per unit area of water delivered over the entire season at each of the gauge stations labelled by their running distance. The average volume per unit area is 12.82 mm/week. Overall the median value for all gauges is comparable other than the very last gauge. The variance in volume per unit area of water delivered increases towards the mid-length of the channel but remains largely constant thereafter. To determine whether the running distance along a canal explains the volume per unit area we take data for all 26 weeks and regress volume per unit area against the running distance. The results of this regression are shown in Table 5 and the low R-squared value suggests that this model is weak at explaining the volume per unit area. The coefficient for running distance is not statistically significantly ($p > 0.05$) indicating that running distance is a poor explanatory variable, alternatively to use the terminology commonly found in literature, statistically there is no head-middle-tail inequity in the tertiary canal 5R during *Kharif* 2015.

A more informative way to examine inequity is to use a summary statistic that captures inequity rather than using the volume (per unit area) at each gauge for each week. For example, the inequity (as measured by the Gini index) for the volume (per unit area) for the data in Fig. 2 is 0.11. Fig. 4a shows the inequity for each week of *Kharif* 2015. Over the season the Gini ranges from 0.00 to 0.18 with an average of 0.09. In three of the 26 weeks the observed inequity is 0 (i.e. perfect equity), an artefact of the closing of the tertiary canal in those weeks. To address the issue of tertiary canals operating in a

Table 5
Ordinary least squares (OLS) regression results for depth (per unit area).

Source	SS	df	MS	Number of obs = 467
Model	5.46240604	1	5.46240604	F(1, 465) = 0.07
Residual	35302.9102	465	75.9202369	Prob > F = 0.7886
Total	35308.3726	466	75.7690398	R-squared = 0.0002
				Adj R-squared = −0.0020
				Root MSE = 8.7132

Depthmm	Coef.	Std. Err.	t	P > |t|	[95% Conf. Interval]	
GaugeRDm	0.0000374	0.0001396	0.27	0.789	−0.0002369	0.0003118
_cons	12.61524	0.8643421	14.60	0.000	10.91674	14.31374

binary mode i.e. either shut or open and flowing at or near capacity, Anwar and Haq (2013) suggested that the Gini should be estimated using cumulative volume per unit area rather than weekly volume per unit area herein referred to as cumulative Gini. Fig. 4a shows the

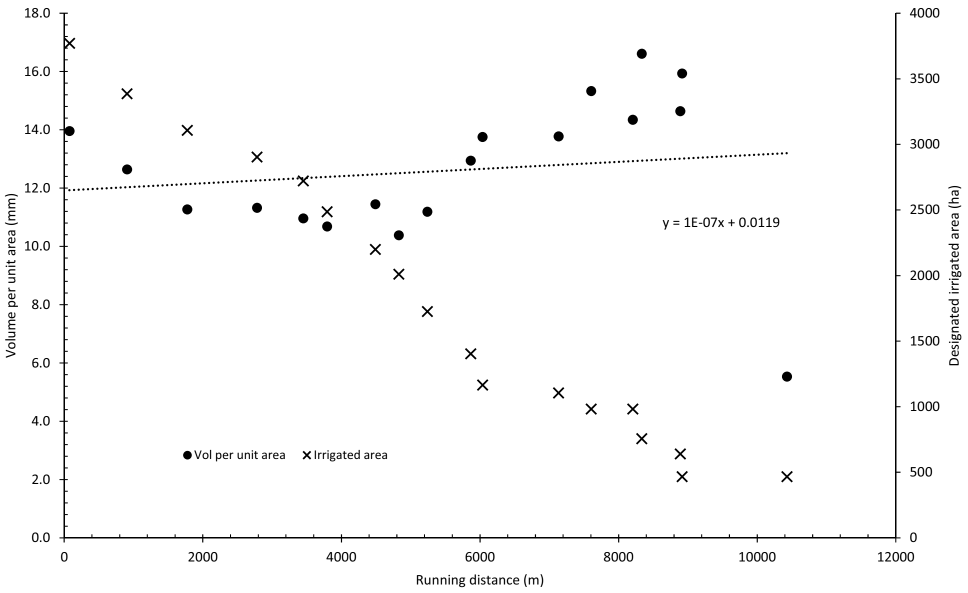


Fig. 2. Volume (per unit area) during *Kharif* 2015 Wk. 1.

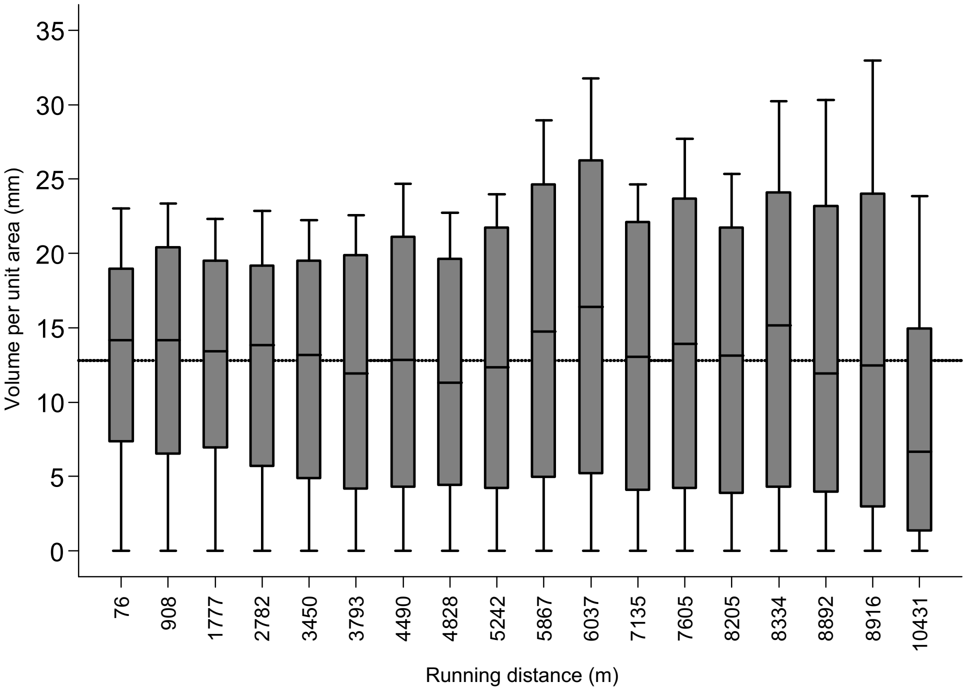
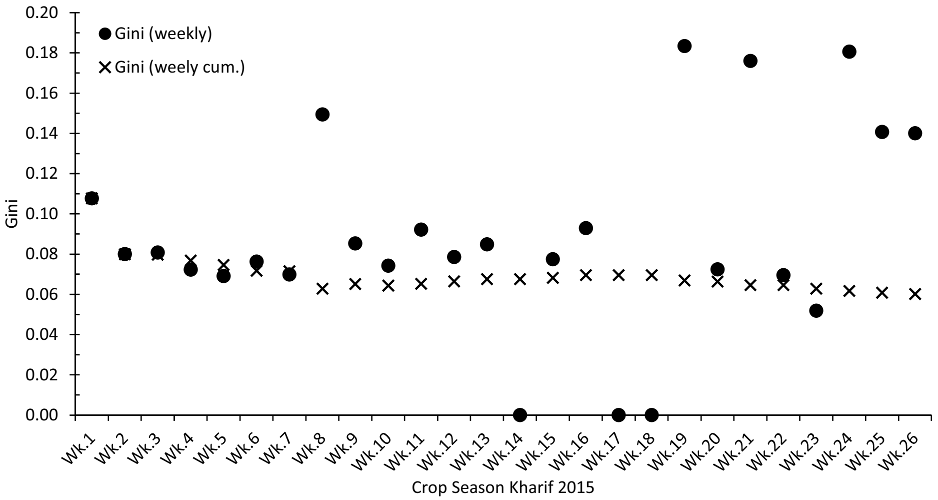


Fig. 3. Box plot of volume per unit area delivered over entire season (*Kharif* 2015).

a) Tertiary canal 5R



b) Secondary canal: Hakra Branch Canal

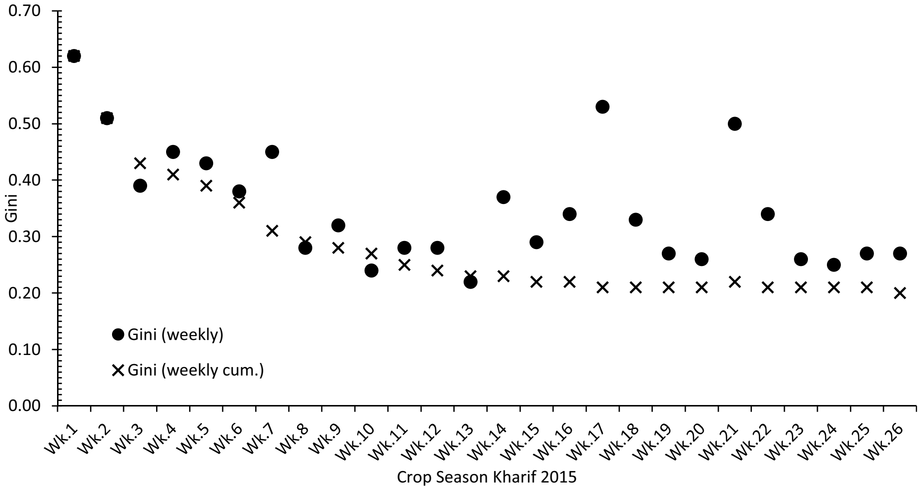


Fig. 4. Inequity in water delivered during *Kharif* 2015. (a) Tertiary canal 5R. (b) Secondary canal: Hakra Branch Canal.

cumulative Gini which varies considerably less and is asymptotic at approximately 0.065. It is important to note that the cumulative Gini does mask inter-temporal variability but nonetheless provides useful insight into the management of the canal system.

The relative change in the Gini is of greater interest than its absolute value. Fig. 4b presents the inequity for the crop season of *Kharif* 2015 for the secondary canal (Hakra Branch Canal) one tier higher in the canal hierarchy. In general the inequity in the secondary canal – Hakra Branch Canal – for *Kharif* 2015 is higher than that in the tertiary canal 5R. The cumulative Gini for Hakra Branch canal is 0.20 as compared to the cumulative Gini for the 5R which is considerably less at 0.065 and contradicts the anecdotal evidence referred to by Anwar and Haq (2013) – albeit this conclusion can only be made for the specific secondary and tertiary canals in this study and not necessarily generalized. Nonetheless the methodology used in this analysis can be applied to any secondary or tertiary canal. If the purpose of a large infrastructure development investment is to improve equity, then such an investment would be better directed at Hakra Branch canal rather than tertiary canal 5R.

An alternative method of placing an index in context is to compare the index against some reference or benchmark value. To estimate a benchmark value of the index for the tertiary canal 5R we return to Table 3 which provides the rated discharge for each of the 26 outlets. Under ideal conditions one could argue that the outlets would supply this rated discharge consistently for the entire crop season. Hence we can use this rated discharge of each outlet to estimate a benchmark for equity. The Gini is scale invariant – one of the axioms (desirable properties) of a measure of equity – therefore converting discharge per unit area to volume per unit area will yield an identical estimate of the Gini of 0.04. This inequity is "hard-wired" in the system, a result of the physical properties i.e. outlet dimensions, canal properties etc. We refer to this as systematic inequity. Fig. 5 shows the observed inequity along with the systematic inequity. We refer to any inequity over the systematic inequity as operational inequity. Considering the end of season (wk. 26) Fig. 5 shows that the design conditions of the canal corresponds to a Gini of 0.04 which we describe as systematic inequity, and compares the observed Gini of 0.06. We describe the difference of 0.02 as operational inequity. This would suggest any development investments in the physical infrastructure may improve at best the systematic inequity, however the operational inequity would require investment in management practices. A system could be managed to over-correct i.e. not only to correct the operational inequity but also to correct the systematic inequity. Improving management may be more cost effective than improving physical infrastructure.

Within the IBIS a typical proxy indicator of equitable distribution of water is the depth of flow at the tail of the canal and/or the discharge in the head of a canal often normalized by capacity (referred to as delivery performance ratio). Fig. 6a shows the weekly average depth of flow at the tail-end of the canal and weekly equity. The canal is designed such that the tail-end should flow at a depth of 0.30 m when the canal flows at capacity. However over the season we observe considerable variation and the depth of flow ranges from 0.00 m to 0.40 m with an average of 0.19 m. Fig. 6a shows a decreasing trend in the Gini (a measure of inequity) with increasing depth of flow at the tail end of the canal supporting the use of tail depth of flow as a proxy indicator. Fig. 6b shows the weekly delivery performance ratio (discharge normalized by capacity) and the weekly equity. Fig. 6b shows there is no apparent relationship between the Gini as a measure of inequity and delivery performance ratio. Table 6 reports the results from a regression with the Gini Index as the dependent and the depth of flow at the tail of the canal and delivery performance ratio as the independent (explanatory variables). The low R-squared value shows this model is weak in explaining inequity (as measured by the Gini). The estimated coefficients in this regression for both depth of flow at the tail and the delivery performance ratio are insignificant (p-value > 0.05) also confirmed by the reported Prob > F = 0.6652 in Table 6. This indicates that depth of flow at the tail-end is not a good performance indicator of equity even though it is the indicator used throughout the Indus Basin Irrigation System.

3.2. Estimating equity using discharge through tertiary canal outlets

Fig. 7 shows the discharge through the outlet estimated using (3) and (4) compared with measurements using flowmeters. Measurements were taken over a period of time i.e. under varying tertiary canal discharges, however only for those outlets which by observation were clearly under free-flowing conditions since (3) and (4) are free-flow equations. In Fig. 7 we set a threshold of ±15% as an acceptable level based on expert opinion. Some observations are outside this threshold, however the normalized average absolute error is 13.80%. Although there is room for improvement in the estimated discharge of the outlets, given that the outlets are generally in a state of poor repair and the construction is often non-standard the reported error is reasonable. Furthermore we have used a con-

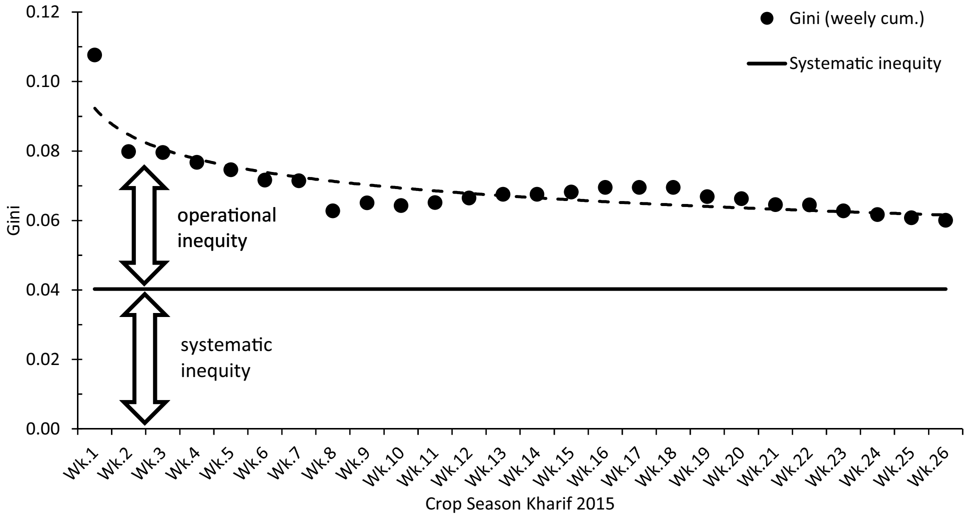
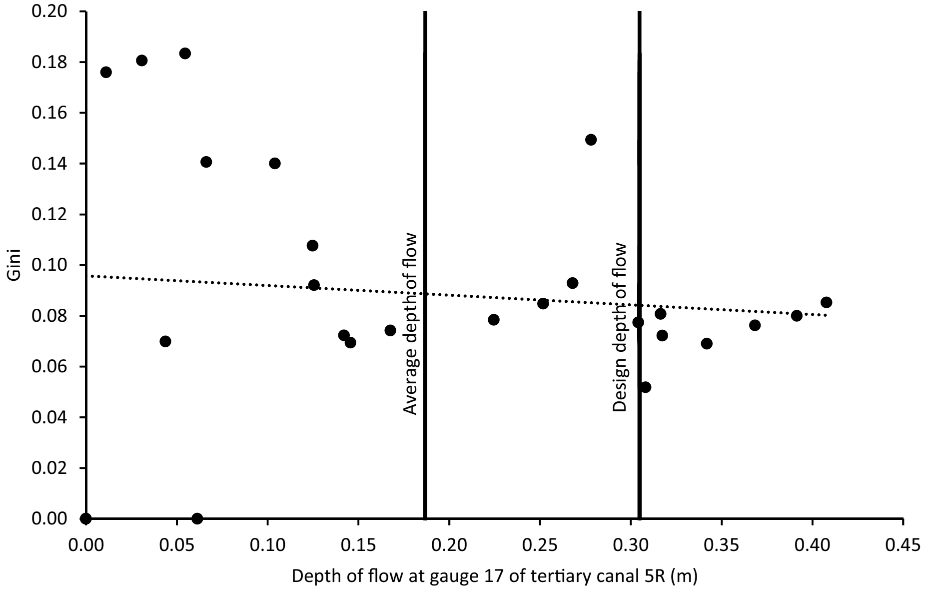


Fig. 5. Systematic and operational inequity.

a. Inequity against depth flow at the tail end of the canal



b. Inequity against delivery performance ratio

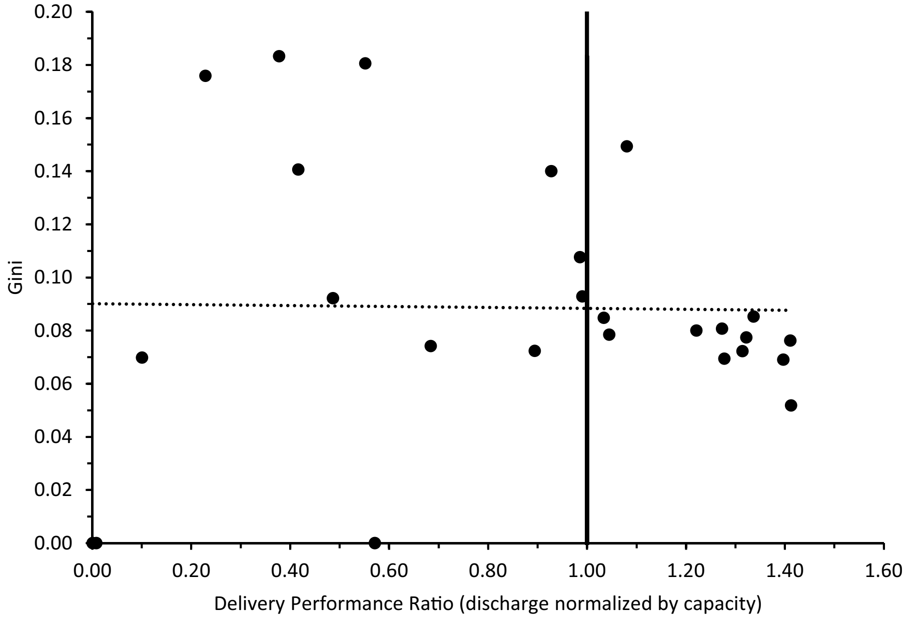


Fig. 6. Weekly inequity. (a) Inequity against depth flow at the tail end of the canal. (b) Inequity against delivery performance ratio.

Table 6
Ordinary least squares (OLS) regression results for equity.

Source	SS	df	MS	Number of obs = 26
Model	0.002163989	2	0.001081995	F(2, 23) = 0.41
Residual	0.059974477	23	0.002607586	Prob > F = 0.6652
Total	0.062138466	25	0.002485539	R-squared = 0.0348
				Adj R-squared = −0.0491
				Root MSE = 0.05106

Gini	Coef.	Std. Err.	t	P > |t|	[95% Conf. Interval]	
Tail Depth_m	−0.1414773	0.1554006	−0.91	0.372	−0.4629479	0.1799933
DPR	0.0348194	0.0448155	0.78	0.445	−0.0578886	0.1275273
_cons	0.0849346	0.0218896	3.88	0.001	0.0396526	0.1302167

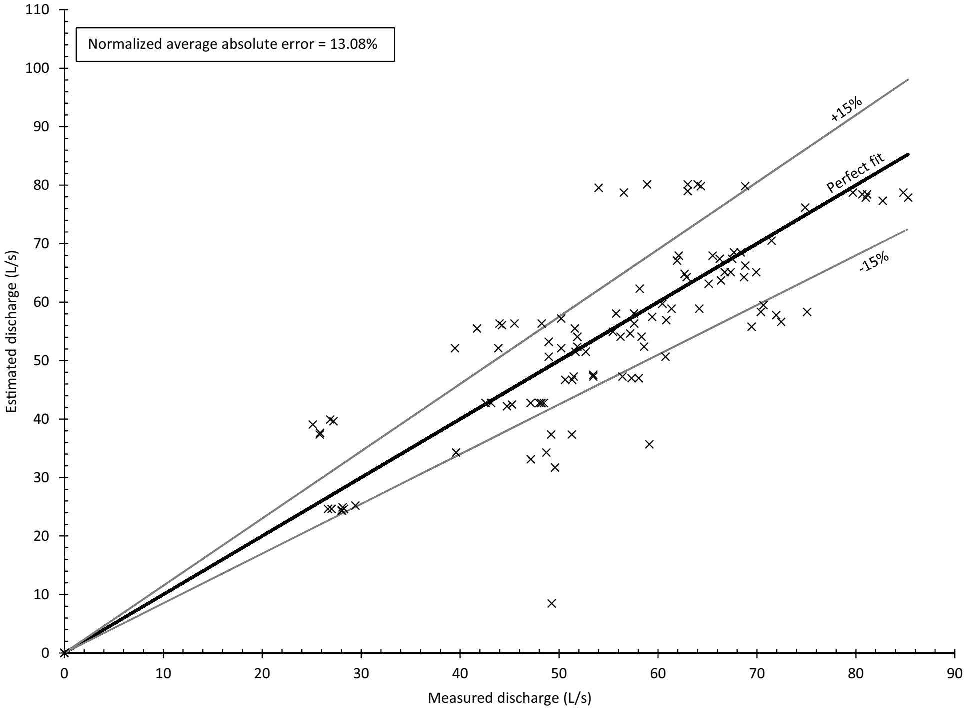


Fig. 7. Estimated versus measured outlet discharge.

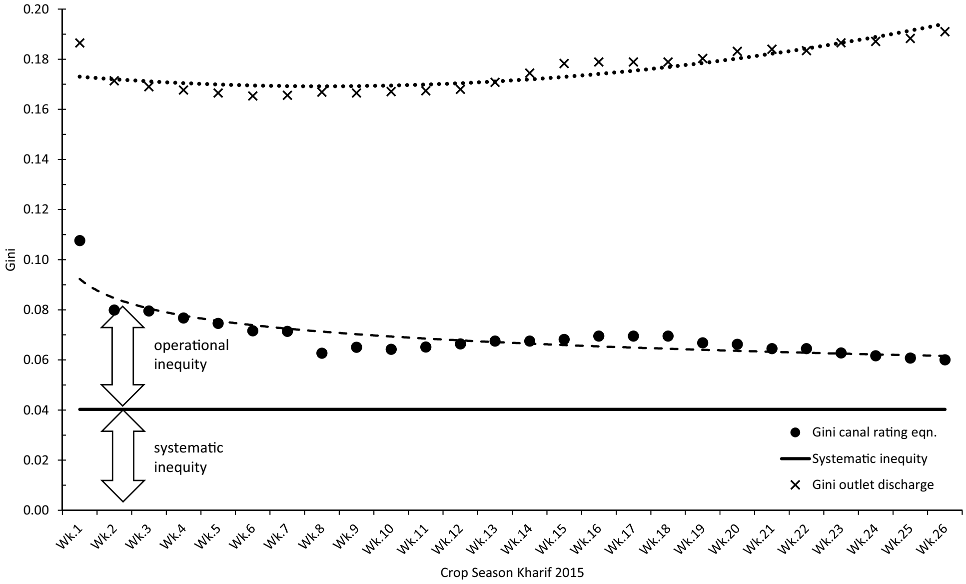


Fig. 8. Inequity estimated using outlet discharge.

stant discharge coefficient for (3) and (4). To improve estimates the discharge coefficient could be calibrated to each outlet, however this would be very time consuming and difficult to scale up. A better alternative might be to standardize the design and construction of outlets such the performance/behaviour of outlets is more deterministic and predictable.

Fig. 8 shows the inequity as indicated by the Gini using estimated outlet discharge for the entire crop season. The estimated outlet discharge is used to estimate cumulative volume per unit area delivered by each outlet. The inequity of this volume per unit area is summarized by the Gini. Fig. 8 also shows the Gini for the cumulative volume per unit area estimated using canal rating equations as presented earlier. Both estimates of Gini are reasonably constant over the season, however the Gini estimated using outlet discharge is considerably greater than that estimated by the canal rating equations. A headline figure being that the end-of-season Gini estimated using outlet discharge is 19% whereas that using canal rating equations is only 6%. Some of this discrepancy can be explained by the error in estimating outlet discharges which was reported in the previous paragraph. There is a further error in estimating outlet discharges due to the fact that some outlets are drowned and a free flow equation would over-estimate the discharge. The next paragraph attempts to provide further insight into this. As described in the literature, equity is acknowledged as of paramount importance. System management and equitable distribution are synonymous and is essentially hardwired into the

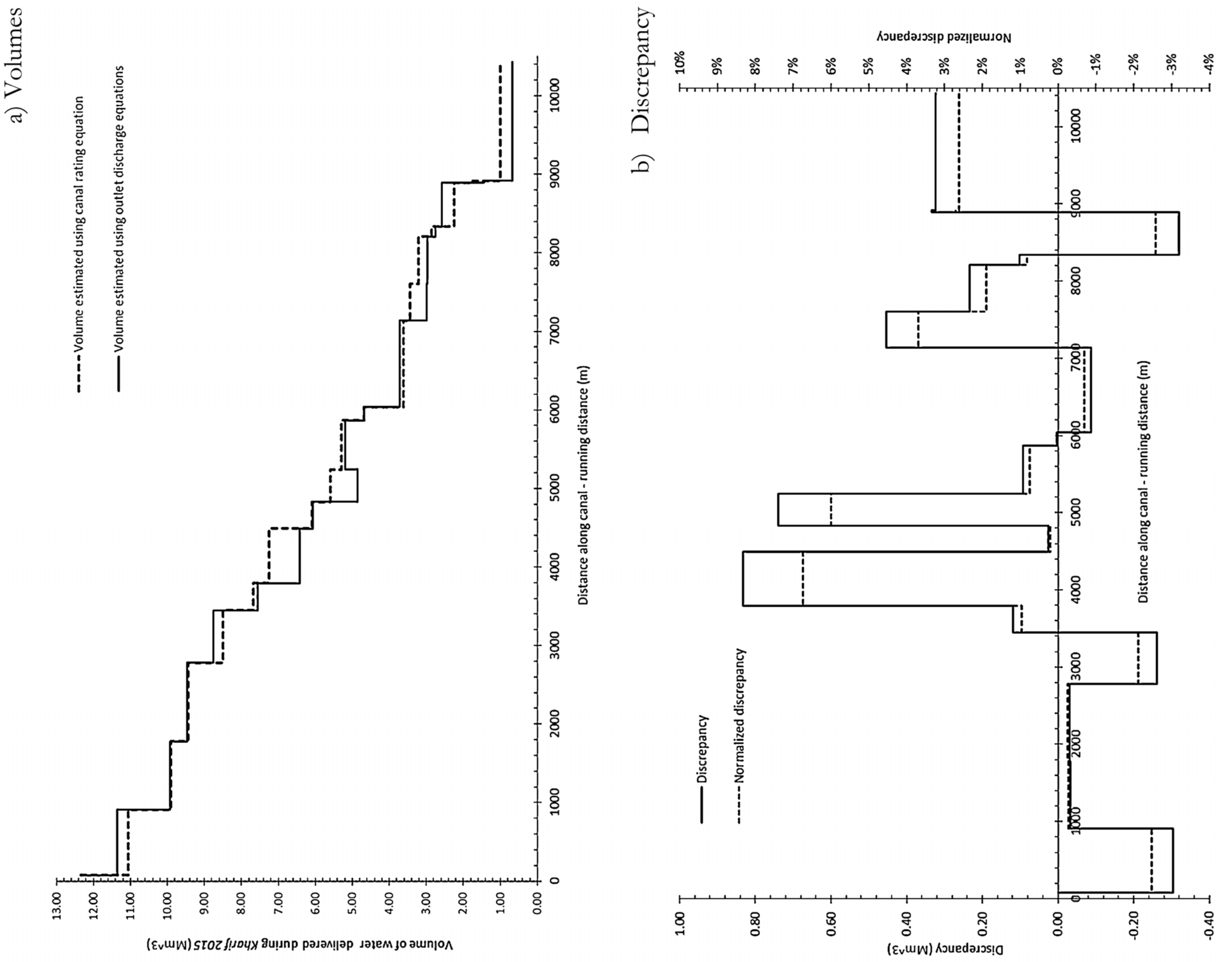


Fig. 9. Volume balance along the canal. (a) Volumes. (b) Discrepancy.

system, hence canals and outlets are all sized to ration the water equitably. However an outlet may be drowned by accident or design by farmers e.g. by not clearing out downstream private or collective watercourses despite this clearly being their responsibility, alternatively a farmer may deliberately restrict the flow in a watercourse to raise the water level and irrigate a relatively elevated field. Under such conditions the equity may deteriorate.

Fig. 9 provides some further insight into the discrepancy between using canal rating equations versus outlet discharge equations. Fig. 9a shows the volume delivered over the entire season by each reach of the tertiary canal. Proceeding along the canal the area irrigated by the canal decreases and one would expect the volume of water delivered to decrease which is the general trend observed in Fig. 9a. Water is abstracted from the tertiary canal at discrete points (outlets) and hence volume delivered is a discontinuous piecewise function of distance along a canal (running distance). The first reach of the canal delivers 12.33 Mm^3 during the season. This corresponds to 1.54 mm/day for 4271 ha and a 26 week season. The capacity of the system as reported earlier is 2.37 mm/day, but the data shows that for certain durations during the season the canal was closed and hence it is intuitive that the volume of water supplied is less than the system capacity. Fig. 9a shows the volume delivered over each reach of the canal estimated using both canal rating equations and outlet discharge equations. Generally there is reasonable agreement as to be expected. However the estimates with canal rating equations shown an anomalous behaviour at 5200 m where the discharge in the canal appears to increase. This would indicate water was actually being added to the canal which was not observed. Hence this would suggest the canal rating equations are not predicting the discharge accurately in this and/or the adjacent upstream and downstream reaches. Some of the discrepancy between the two estimates of discharge can be explained by;

- Errors in estimating discharge in the canal using a semi-empirical rating curve.
- Errors in estimating discharge of outlets under free flow conditions.
- Outlets not flowing under free flow conditions as assumed.
- Incorrect application of flume equation versus orifice equation or vice versa.

Furthermore water theft, tampering and pilferage are also known to exist and is widely reported. Volume estimates using canal rating curves would incorporate any such activities, whereas estimates using outlet discharge equations would be unable to account for such abstractions of water. Fig. 9b reports the volume balance discrepancies and also the discrepancy normalized by the volume delivered at the head of the canal (12.33 Mm^3). The maximum discrepancy is 0.83 Mm^3 in the 4000 m reach followed closely by the adjacent reach where the discrepancy is 0.74 Mm^3. In normalized terms the error is +7% i.e. canal rating equation estimates are greater than outlet discharge equation estimates by +7% and −3% i.e. canal rating equations estimates are less than outlet discharge equation estimates by −3%. At the very least Fig. 9b identifies reaches of the canal where further attention is needed to estimate volumes, ensure that outlets are flowing freely and/or whether there are any other activities such as tampering and pilferage.

4. Conclusion and recommendations

In this paper we have demonstrated the application of summary statistical measures of equity to the tertiary canal/outlet level. The volume (per unit area) is estimated using two techniques. There is a difference in the estimated discharge depending on the methodology employed. However irrespective of the methodology used to estimate volume per unit area, neither indicate a decrease in volume per unit area with distance along the canal. Hence at least for the case of the tertiary canal 5R during *Kharif* 2015 we do not observe the head-middle-tail inequity often cited and generalized in the literature. We have also shown that although the depth of flow at the tail end of a canal is widely used in the Indus Basin Irrigation System as a proxy indicator, this is in fact a poor indicator of equity. We reaffirm that measuring flows within a canal where dedicated flow measurement structures do not exist and one has to resort to rating equations and/or measuring discharge through outlets still poses a challenge. However it is still possible to obtain reasonable estimates and thereby determine the inequity in the system. The advantage of using a quantitative measure of inequity such as the Gini as opposed to the qualitative description hitherto more common is that it allows alternative comparisons to be made. We compare the inequity in the tertiary canal with that in the upper tier secondary canal and also with inequity had the system been operated “to design”. Thereby we have introduced new concepts of systematic and operational inequity.

Up scaling the installation of electronic equipment at the density of approximately 2 per 1000 m, (instrument density in this work), throughout the Indus Basin Irrigation System would be prohibitively expensive. Exploring more cost-effective solutions and the impact of compromising on spatial, and/or temporal resolution of data acquisition is the subject of on-going work. Estimations of both canal flows and outlet discharges needs to be improved further if one is to convince practitioners and policy makers of the value of such research. This technology could allow for disseminating management information namely; discharge, volumes and summary statistics on equity disaggregated by individual outlet level and on a weekly basis to coincide with the *warabandi* weeks. Individual farmers could identify with this information as each farmer knows which outlet s/he receives water. The impact that such information could have on the perceptions of the farmer on how water is being managed and also the interactions with the irrigation agencies could also be the subject of further work.

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