# *Socio#Hydrology of Channel Flows in Complex River Basins: Rivers, Canals, and Distributaries in Punjab, Pakistan*



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**Special Section:**
Socio-hydrology: Spatial and Temporal Dynamics of Coupled Human-Water Systems

**Key Points:**
- Coupling historical geographic and statistical analysis makes an important contribution to the theory and methods of socio-hydrology
- Comparing channel flow entitlements with deliveries sheds light on patterns of surplus and deficit at the river inflow, canal, and distributary scales
- New technologies of distributary discharge measurement, data relay, and analytics display the surpluses and deficits of traditional irrigation scheduling (*warabandi*) for real-time feedback

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# Socio-Hydrology of Channel Flows in Complex River Basins: Rivers, Canals, and Distributaries in Punjab, Pakistan

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**Abstract** This paper presents a socio-hydrologic analysis of channel flows in Punjab province of the Indus River basin in Pakistan. The Indus has undergone profound transformations, from large-scale canal irrigation in the mid-nineteenth century to partition and development of the international river basin in the mid-twentieth century, systems modeling in the late-twentieth century, and new technologies for discharge measurement and data analytics in the early twenty-first century. We address these processes through a socio-hydrologic framework that couples historical geographic and analytical methods at three levels of flow in the Punjab. The first level assesses Indus River inflows analysis from its origins in 1922 to the present. The second level shows how river inflows translate into 10-daily canal command deliveries that vary widely in their conformity with canal entitlements. The third level of analysis shows how new flow measurement technologies raise questions about the performance of established methods of water scheduling (*warabandi*) on local distributaries. We show how near real-time measurement sheds light on the efficiency and transparency of surface water management. These local socio-hydrologic changes have implications in turn for the larger scales of canal and river inflow management in complex river basins.

## 1. Introduction

The Indus River basin in Pakistan is one of the major water resources laboratories in the world (Akhter, 2017; Gilmartin, 2015; Meadows & Meadows, 1999; Mustafa, 2013; Yu et al., 2013). It belongs to a class of intensively studied complex river basins that have multiple scales of nested water management (Molle & Wester, 2009; Pulwarty, 2015; Reibsame et al., 1995). Its hydrologic processes link glaciated mountain valleys with monsoon plains and a deltaic coastline, each of which has distinctive water management regimes. In historical geographic terms, its irrigation systems date from Indus Valley civilization through Buddhist, Sultanate, Mughal, Sikh, colonial, and postcolonial eras (Naqvi, 2013). In the plains environment of Punjab province, its socio-hydrologic processes range from international transboundary agreements to multiple scales of irrigation management that have generated enormous bodies of research (Wescoat et al., 2000) (Figure 1).

These studies have helped make the Indus River basin in Pakistan a center of social and hydrologic research, though not yet explicitly a center of socio-hydrology. Socio-hydrology contributes to the International Association of Hydrologic Science decade titled *Panta Rhei*, which takes its inspiration from the Greek philosopher Heraclitus (Montanari et al., 2013). It is noteworthy that the middle Indus valley was a frontier of Greco-Buddhist Gandharan culture that articulated a philosophy of impermanence, suffering, and enlightenment, akin to the *Panta Rhei* aims, which drew scholars and pilgrims from as far away as China in the fifth century (Legge, 1965).

An early essay on socio-hydrology identified three main lines of research: (1) historical (across time); (2) comparative (across space); and (3) processual (across disciplines and models) (Sivapalan et al., 2012). This paper shows how the first two types can be combined in an historical geographic approach (Michel, 1967; Wescoat, 1999). Research on socio-hydrology emphasizes the third approach, which entails quantitative coupled modeling of social scientific and hydrologic processes (e.g., Troy et al., 2015). Quantitative coupled modeling is essential for the field, though in some ways it can reinforce the separation between social and hydrologic processes. For example, channel flows are not so much coupled human and hydrologic systems, as they are a jointly socio-hydrologic phenomenon. This point is reinforced by a recent bibliometric study


**Figure 1.** Irrigation and river network of Punjab (source: authors).

that documents strong associations between socio-hydrology and management, which is also an integrated vis-à-vis coupled practice (McCurley & Jawitz, 2017). A complementary approach to coupled modeling would thus treat water processes, in this case flows, as jointly social and hydrological. A second issue with coupled quantitative models is that they may treat historical processes somewhat reductively as time series, and geographical processes as spatial patterns in ways that eclipse the interpretive power of qualitative historical geographic research (exceptions include Di Baldassarre et al., 2015; and cf., Wesselink et al., 2017). Conversely, rigorous historical geographic research on the Indus has rarely engaged quantitative water data analysis, and can benefit greatly from its insights.

This paper seeks to demonstrate this new type of coupled research that links qualitative historical geographic research with quantitative analyses of channel flows at three levels: river inflows, canal deliveries, and distributary flows on the irrigated plains of the Punjab province in Pakistan (Figure 2). At each level, we begin with a brief historical geographic account of current flow measurement and management. We then analyze a key flow dataset at that level to show how it sheds light on contemporary socio-hydrologic issues.

These historical geographic and quantitative analyses could yield separate papers at each level, but here we link them to demonstrate the potential of coupled qualitative and quantitative inquiry across scales. We note that groundwater, water quality, and agricultural production are closely related aspects of Indus basin water management that are not addressed here (see Siddiqi & Wescoat, 2013). We focus on surface flows to demonstrate this new approach, which can be extended to incorporate related processes in future research.

## 2. Indus River Inflows to Pakistan

River flows are generally treated as hydrologic phenomena, i.e., as the natural discharge of a river basin drainage network. Variation in river flow rates and extreme flows—floods and hydrologic droughts—trigger human curiosity, concern, and attribution to social as well as hydrologic causes. River flow measurement locations, units, and analytic methods are historically chosen to shed light on these processes and propositions.

### 2.1. Early River Flow Measurement in the Indo-Gangetic Plains

The origins of river flow measurement in the Indus are unknown. There is no evidence of ancient or medieval gauges or stepped masonry terraces (*ghat*s) along rivers in the Punjab. Ancient knowledge of flow regimes is implicit in the massive check dams (*gabbarband*s), inundation canals, and urban sewer channels of the Harappan period, but no flow recording methods or records survive (Joshi, 2008; Mate, 1998). Floods and droughts are mentioned in chronicles of the Sultanate (11th–15th c CE) and Mughal periods

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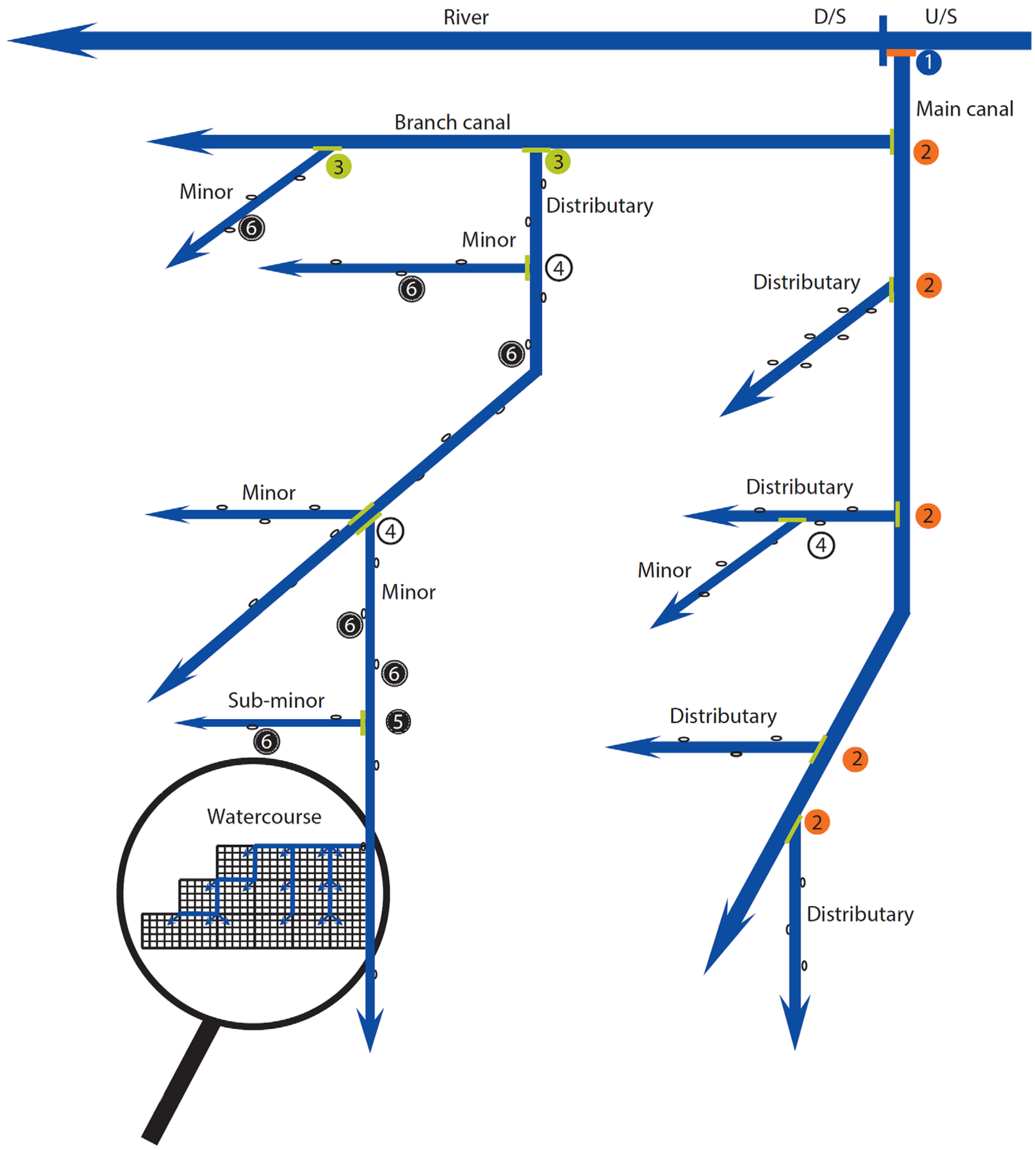


**Figure 2.** Surface water channel system (source: Yu et al., 2013, 43).

(16th–18th c CE), but authors emphasized their impacts on ferries, fords, and food supplies, rather than their frequency, duration, or magnitude (Agrawal, 1983; Habib, 1999).

The first modern records of river discharge in cubic feet per second in the Indo-Gangetic plains were compiled for navigation purposes on the lower Ganges (Rennell, 1783, p. 356). They extended to irrigation development planning in the East India Company's restoration of Delhi Sultanate canals, construction of the new Ganges Canal (Cautley, 1841), and irrigation planning for the Punjab plains soon after annexation in 1848 (Baird-Smith, 1849).

As irrigation development proceeded, flows were converted from cusecs to depths and then volumes (i.e., to feet and acre-feet). Engineers in India converted the cusecs needed to irrigate a given area of land to an equivalent depth of irrigation water known as the "duty of water" or delta ($\Delta$) (Buckley, 1905; Wescoat, 2013). The acre-foot concept originated in New Mexico where pioneering water resource geographer John Wesley Powell explained that people, "… did not understand, second-feet—that is to say, cubic feet per second—that both were indefinite and uncertain terms of measurement to many people; so we have devised a new unit of measurement, and it has rapidly gone into use within the last 5 or 6 months through the technical journals and among the people in the West. An acre-foot of water is an acre of water a foot deep" (Powell in U.S. Congress, 1888–1889, pp. 108–109). Acre-feet became the standard units for recording river inflows for irrigation purposes on the Chenab and Jhelum Rivers by 1922.

Why 1922? This was a period of intensive irrigation development in Punjab and Sindh following WWI. Upstream, the Sutlej Valley Project was designed to replace ancient seasonal inundation canals with perennial canals in Bahawalpur State (Indian Irrigation Commission, 1901–1903). Downstream, Sindh water planners proposed to build the huge Sukkur barrage on the Indus main stem, and were deeply concerned about upstream water depletion. These concerns were aggravated by historic low flows in 1918 (Haines, 2017, p. 15). An Indus Discharge Commission created in 1921 stressed the vital role of scientific measurement of river flows, which was reaffirmed and updated by the Anderson Committee in 1935 (Michel, 1967, pp. 118–119).

In summary, Indus River inflows to the Punjab province of Pakistan have come to be measured daily in cubic feet per second (cusecs) that are used to designate low, medium, and high flood stages; and that are converted into million acre-feet (MAF) for irrigation planning, policy, and modeling purposes. Because the two primary purposes of measurement are to prepare for flood flows and to allocate shares of the river for water supply, flow records are inherently socio-hydrological. The next section examines the record of volumetric flows on the Indus and its six major tributaries.

### 2.2. Inflows From the Eastern Rivers

The Indus Waters Treaty of 1960 awarded the three major eastern tributaries of the Indus—Ravi, Beas, and Sutlej, which rise in the western Himalayas and Tibet—to India, which led to precipitous drops in flows downstream in Pakistan (Figure 3). Not surprisingly, these flows are regarded as more social than hydrological in Pakistan. Any inflows to Pakistan after the initial 10 year transition period from 1960 to 1970 are the product of excess monsoon runoff and return flows. Large dams and link canals were constructed on the Indus and Jhelum Rivers to transfer water to mitigate these depletions on the eastern rivers. The period of record used for planning on the eastern rivers is thus relatively short, from 1976 to the present, which marks the completion of Tarbela Dam and reservoir on the Indus main stem. Five and 10 year average inflows are used for planning purposes (NESPAK, AHT, & Deltares, 2015). Residual flows continue to decline but are not altogether incidental for downstream ecosystems and settlements in Pakistan.

Figure 3 indicates the rapidly declining rate of discharge on the Ravi and Sutlej. Ravi inflows at Balloki Barrage display a step function beginning at roughly eight MAF per year in the 1970s, dropping to four or

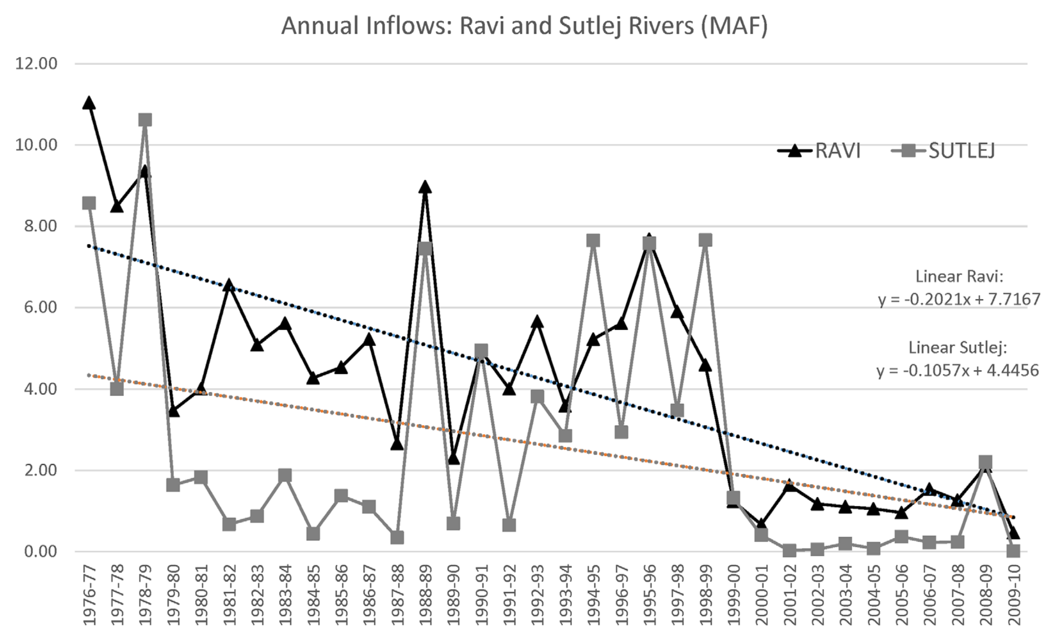


**Figure 3.** Annual inflows: Ravi and Sutlej Rivers. Plotted from WAPDA data.

five MAF until 1999, and less than two MAF thereafter. Monsoon rains still trigger flood events as occurred in 1988 when earthen bunds along the river were breached to protect the city of Lahore (Mustafa & Wescoat, 1997). Complaints were raised about inadequate flood warning and control upstream and inadequate preparedness downstream.

Sutlej River inflows at Sulemanki Barrage also declined dramatically in the 1970s, though with a different pattern than occurred on the Ravi. The Sutlej displays much higher variability than the Ravi (annual coefficients of variation = 0.83 compared with 0.47). It experienced a low flow period in the 1980s, followed by erratic high flows in the 1990s, and negligible inflows thereafter. Flows increase downstream of Sulemanki Barrage due to inputs from link canals, monsoon runoff, and irrigation return flows. In this respect, the eastern Punjab rivers downstream from the rim stations are less like rivers than the canals examined in a later section of this paper. The 1988 flood was all the more shocking on the Sutlej in comparison to its previous decade of low flows.

### 2.3. Inflows on the Western Rivers

The Indus Waters Treaty of 1960 allocated flows of the three western rivers of the Indus basin—the Indus main stem, Jhelum, and Chenab—to Pakistan. Their glaciated headwaters rise in extraordinarily complex terrain of the Hindu Kush, Karakorum, and western Himalayas in Afghanistan, India, and China/Tibet. The general expectation in Pakistan is that these rivers should carry their full natural hydrologic flow, with upstream uses strictly limited by treaty provisions. The expectation upstream in India, by comparison, is that it has the right to develop numerous run-of-river hydropower facilities and uses allowed under the treaty. The balance between their socio-hydrologic perspectives on the rivers vary.

A major issue that the treaty recognized but did not fully address is that the upper reaches of all three rivers lie in the disputed territories of Gilgit-Baltistan and Azad Jammu and Kashmir controlled by Pakistan, and Jammu and Kashmir controlled by India. The long-term internal water needs and wants of these territories have been evolving since the signing of the Indus Water Treaty. Moreover, the effects of climate change on the snow and ice hydrology of all rivers—i.e., floods, droughts, and shifts in the timing of runoff—raise growing concerns upstream and down. We illustrate how these anxieties and disputes have shaped the socio-hydrologic interpretation of western river inflows below.

#### 2.3.1. The Indus River Main Stem

It contributes by far the largest inflows into Punjab, averaging 62 MAF per year from some 166,000 $km^2$, most of it through snowmelt in May–July followed by an increasing fraction of icemelt through July and August (Yu et al., 2013, pp. 61–75). A plot of annual inflows from the Indus main stem indicates a significant decline over the period of record (Figure 4), particularly during the summer *kharif* planting season. In terms of monthly river inflows that have relevance for canal deliveries, the highest coefficients of variation are observed for the onset of melting in May (0.298; with an increasing mean) and monsoon recession in August (0.235; decreasing mean).

It is noteworthy that two of the three extreme values on record were recorded in a high-low sequence during the filling of Tarbela reservoir (1973–1975). Tarbela reservoir has less than a year of storage which limits its role in interannual water management. Although there are no regulatory works on the main stem upstream of Tarbela Dam at present, two major projects—Dasu and Diamer-Bhasha dams—have been initiated with a mix of Chinese, World Bank, and domestic funding. However, these and related China-Pakistan Economic Corridor (CPEC) projects have also been challenged by India as occurring in disputed territory (Government of India, 2017; Pakistan-China Institute, 2017). The social dimension of socio-hydrology thus extends into the realm of geopolitics on the western as well as eastern rivers (Adeel & Wirsing, 2017; Haines, 2017).

#### 2.3.2. The Jhelum River

It rises in the Pir Panjal range, flows through the valley of Kashmir and the city of Srinagar, receiving tributary waters from the Kishenganga (Neelum) River before emptying into Mangla reservoir, which was constructed in 1961–1967 following the signing of the Indus Waters Treaty. Its socio-hydrologic complexity is amplified beyond that of the Indus main stem. The Jhelum yields an average of about 23 MAF per year, primarily from snowmelt (Archer & Fowler, 2008). It has significant annual variability and a slight downward trend in flows over the period of record (annual coefficient of variation = 0.20) (Figure 4).

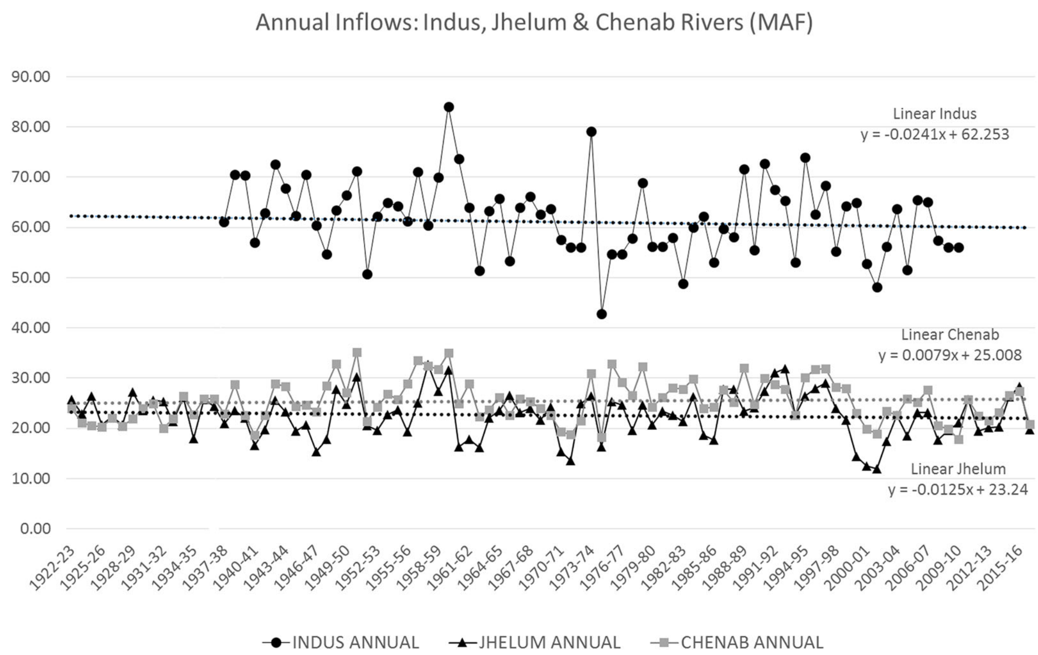


**Figure 4.** Annual inflows: Indus, Jhelum, and Chenab Rivers. Plotted from WAPDA data.

The Jhelum is known as an "early riser," as its meltwaters begin in March and April before peaking in June and July, a month earlier than the Indus. Warming scenarios are expected to shift the hydrograph to earlier discharge, and that is what one observes with increasing March and April discharges, followed by decreasing June and July discharges. What may complicate these timing trends are an array of hydropower projects underway and proposed upstream of Mangla Dam by India and Pakistan. Upstream projects affect flow rates if not volumes to downstream channels, as well as environmental flows, which was litigated in the Indus Waters Kishenganga Arbitration (Permanent Court of Arbitration, 2013).

#### 2.3.3. The Chenab River

It delivers about 25 MAF per year at the Marala Headworks, and it has a higher proportion of rainfall to snowmelt than the Indus or Jhelum. Overall, annual inflows appear relatively stable over the period of record (annual coefficient of variation = 0.16) (Figure 4). In contrast with the other two rivers, the Chenab's recent decade of flows are most often below the mean, which raises water concerns downstream. Some monthly inflows have higher variability than in the other western rivers, particularly the months just before (March and April) and just after the monsoon (September–December) (coefficients of variation ranging from 0.32 to 0.47). Each low and high flow anomaly sparks concerns that human agency as well as hydrologic processes are involved upstream and that somehow India can affect water use beyond the limits of the Treaty. Pakistan has lodged complaints about the Ratle Hydropower Project and other proposed projects on the Chenab and its tributaries (World Bank, 2017).

### 2.4. River Inflows Summary

Interpreting river inflows as jointly social and hydrologic applies to each of the rivers of Punjab, albeit in different ways. Some commentators ascribe fluctuations in flow to hydropower development, climate change, and incremental upstream water uses—blurring the simplistic distinction between hydrologic flows in the western rivers and social flows in the eastern rivers. These trends and complications are likely to increase over time. India has many planned hydropower reservoirs on the upper Chenab and Jhelum Rivers and their tributaries (see the exchange between Briscoe (2010) and Iyer (2011)). Two of these projects have been formally disputed. The Baglihar dam and reservoir on the Chenab was addressed by a special expert appointed by the World Bank. A second dispute arose over the Kishenganga Dam on the Neelum-Jhelum River, and an award was reached by the Permanent Court of Arbitration (2013). Fresh disputes arose in 2016–2017 over Jhelum and Chenab run-of-river projects, which were forwarded to the World Bank, but that remain stalled as India calls for a neutral expert and Pakistan for arbitration (World Bank, 2017). Less attention has been given to the Kabul River which has not had an international agreement since 1921(League of Nations, 1921), notwithstanding proposals for multiple dams upstream in Afghanistan. In addition, Pakistan has planned an Indus River cascade with support from China in territory India regards as disputed that would transform the largely free-flowing upper Indus main stem into a regulated river cascade with greater control over flows into Tarbela reservoir and to downstream canal commands, which is the focus of the next section (Siddiqi et al., 2012).

## 3. From River Inflows to Canal Discharge

"God meant rivers to feed canals," James Brindly, 18th c., cited by East India Company Engineer, Richard Baird-Smith (1849, p. 106).

The historical geography of canal irrigation in Punjab indicates that the earliest irrigation canals during the protohistoric period were seasonal inundation channels. Perennial canals were constructed during the reign of Sultan Firoz Shah Tughluq (d. 1388 CE) followed by the Mughal ruler Shah Jahan (d. 1666 CE) and his nobles (Wescoat, 1999). There are few surviving textual records of these irrigation projects, aside from appointment letters for canal officers (*mir-i ab*) (e.g., Habib, 1999, p. 67). Codification of customary water law in Punjab mentioned the widespread use of physical outlets and time periods to administer canal shares, but not flows *per se* (Tupper, 1881).

From the late-nineteenth century onward, inflows have been measured in daily cusecs for operational purposes, and converted into volumes (MAF) for planning and modeling purposes. Canal operations employ 10-daily time intervals (three per month) that are reported in cusecs and MAF. The 10-daily interval was deemed practical for irrigation scheduling, volumetric allocation, and duty of water calculations for large blocks of land (Willcocks, 1889/1913). Bellasis (1913) noted that the 10-daily average was easy for *zilladar*s and irrigation officers to calculate in the field, which underscores the link between social practicality and hydrologic science that was also observed in the volumetric allocation of river inflows in MAF.

Each new canal necessitated fresh estimates of water supply and demand within its command area. As discussed above, historical data have been the primary basis for adjusting entitlements, beginning in 1921 with the Indus Discharge Commission, followed by the Anderson Committee in 1935, the Rao Commission in 1941–1942, and the Indus Waters Treaty in 1960. Current canal entitlements are based on the 1991 Water Apportionment Accord, Article 14.

A key point for present purposes is that the 10-daily time interval (measured in 1,000 s of cusecs) uses the baseline entitlement period of 1977–1982, which are the 5 years following completion of Tarbela Dam, with pro-rata adjustment of entitlements to share hydrologic surpluses and shortages. The reference period of 1976–1982 excluded extreme events on the Indus in 1973–1975 and was regarded as a period of relatively stable inflows (M. Ahmed, personal communication, 2017). From the previous section, we note that annual inflows during this period were slightly lower than average on the Indus (−5.7%), average on the Jhelum (−0.9%), and above average on the Chenab (+8.2%).

Ten-daily flow data reveal a system with large variations in what is planned and what actually happens, as shown through a systems-level characterization of the 25 main and branch canals that comprise the surface irrigation system in Punjab. Ten-daily flow data reported by the Punjab Monitoring and Implementation Unit (PMIU) over the last decade (2007–2016) allowed us to quantify two key performance measures related to temporal and spatial aspects of surface water deliveries.

### 3.1. Supply Reliability: Uniformity of Delivery Over Time

The first measure characterizes how often the entitlement and delivery flows are matched. The supply reliability, $a_i$ for the ith 10-day period is defined as:

$$a_i = \frac{e_i - d_i}{e_i}$$

where $e_i$ is the entitlement (in cusecs) and $d_i$ is the measured delivery (in cusecs) in period i. In an ideal system, the supply reliability should be steady and uniform throughout the irrigation system.

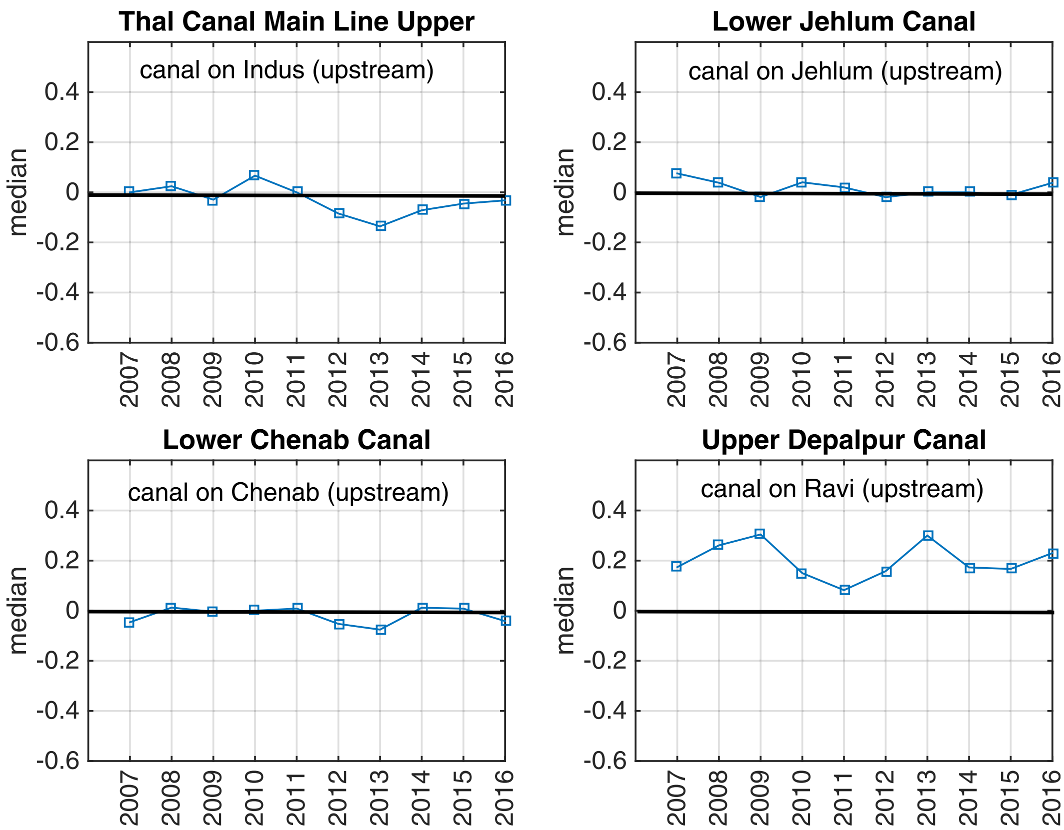


**Figure 5.** Median $a_i$ for *kharif* season (April to September) in the years 2007–2016. A median value close to 0 exists when deliveries equal entitlement in the season; a median value above zero is when deliveries are lower than entitlements; below zero is when deliveries are greater than entitlements.

The median of $a_i$ in a given season, $m_a$, can be used as a measure of on-time delivery. This measure is a modified form of the "dependability" metric introduced by Bolden (1990) for irrigation systems, defined as the ratio of the delivered amount of water to the amount scheduled.

Given the inflows discussion above, one would expect reliability to be greater on the western rivers than the eastern ones, and on the Indus as compared with the Jhelum and Chenab. Figure 5 shows $a_i$ for four canals during the period 2007–2016, which support some but not all of these expectations. For example, the data analysis shows that for several canals the median is frequently above or at zero indicating that they almost always operate in deficit (such as the Upper Depalpur Canal fed by a Chenab River link canal, shown in Figure 5). In other cases, the median is negative (such as for Thal Canal on the Indus main stem from the year 2012 and onward) indicating a higher level of deliveries than the entitlements for those canals. In the full analysis of 25 canals, we found that while for some canals the year-to-year change is small (such as for Lower Bari Doab Canal, Lower Depalpur Canal, and Lower Jhelum Canal). Canals in central Punjab may benefit from inflows from link canals. However, other canals that lie further downstream on the Indus main stem have large fluctuations in the median $a_i$ (such as in Muzaffargarh Canal and D. G. Khan Canal).

These deviations between entitlements and what is actually delivered over time have important implications. Timing of irrigation supplies is critical for crop yields, and low dependability of supply adversely affects productivity. In a system where operators are adjusting entitlements each year based on seasonal forecasts, one would expect that year after year the process would improve such that the difference between entitlement and delivery would go down over time. The system operation should become more and more reliable, i.e., the median $a_i$ should get smaller over time. The 10-year time horizon examined here, while not large enough for a thorough assessment, does not show a trend of increasing dependability or, by extension, "learning" in canal forecasting and deliveries.

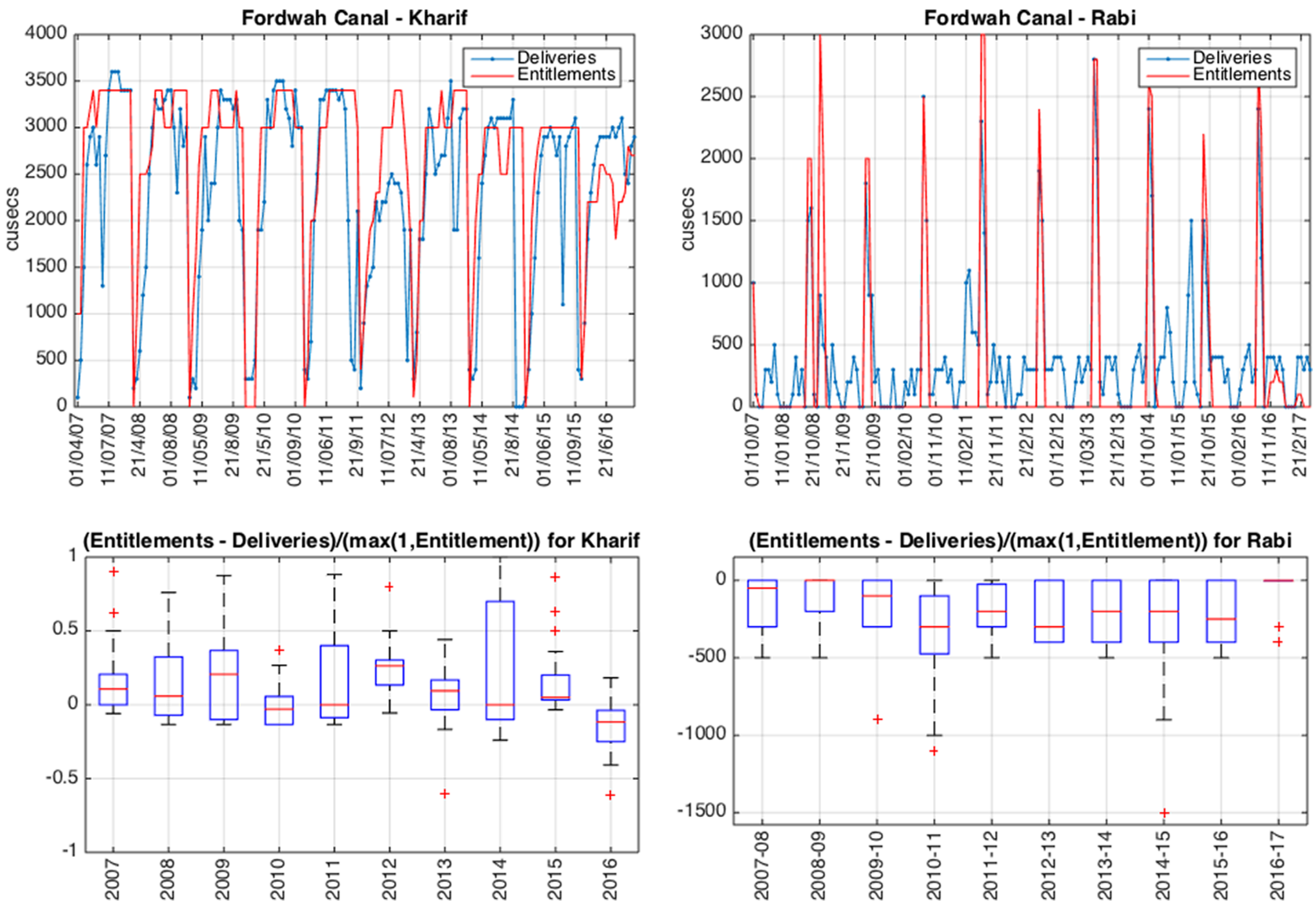


**Figure 6.** Row 1: Irrigation delivery and entitlement data reported for Fordwah Canal in *kharif* and *rabi* seasons (2007–2016). Row 2: Box and whiskers plots of $a_i$ for *kharif* and *rabi* seasons (2007–2016).

Figure 6 shows the recorded seasonal deliveries and entitlements data for Fordwah canal in the Sutlej-Bahawalnagar irrigation division as an illustrative case. Differences in 10-daily deliveries and entitlements vary significantly by season, with *kharif* (summer) and *rabi* (winter) consistently exhibiting different patterns of variation. The timing of Rabi season deliveries, which are critical for agricultural productivity, are consistently longer than the timing of entitlements. It can be noted that while in *kharif* the balance remains positive, indicating delivery deficits, the *rabi* season year after year has negative balance (i.e., delivery surpluses). However, the surplus deliveries in the *rabi* season are less synchronized with times of entitlement.

### 3.2. Equity: Spatial Uniformity of Delivery

The second measure of performance used to characterize the irrigation system is equity, defined as the spatial uniformity of the ratio of the delivered amount of water to the scheduled amount (Molden & Gates, 1990). The volumetric allocation to different canals varies with the size of their command area. The ratio of delivery to scheduled volume for each canal, however, should be similar in an equitable system for a given season and year. The analysis, however, reveals that in the period 2007–2016, the interquartile range of this ratio in the 25-canal system has increased steadily during the *kharif* irrigation season, as shown in Figure 7.

The 10-daily canal flow data in Punjab's irrigation canals reveal a set of key features. First, the system by and large operates in deficit, which reflects the historical geographic practice of deficit irrigation, which has its roots in the colonial emphasis on "protective" water spreading rather than "productive" irrigation (Gilmartin, 2015; Wescoat, 2013). Second, there are some consistent and curious features of surplus deliveries, which may be explained through a combination of sanctioned operational procedures, hydraulic conditions, and/or preferential practices.

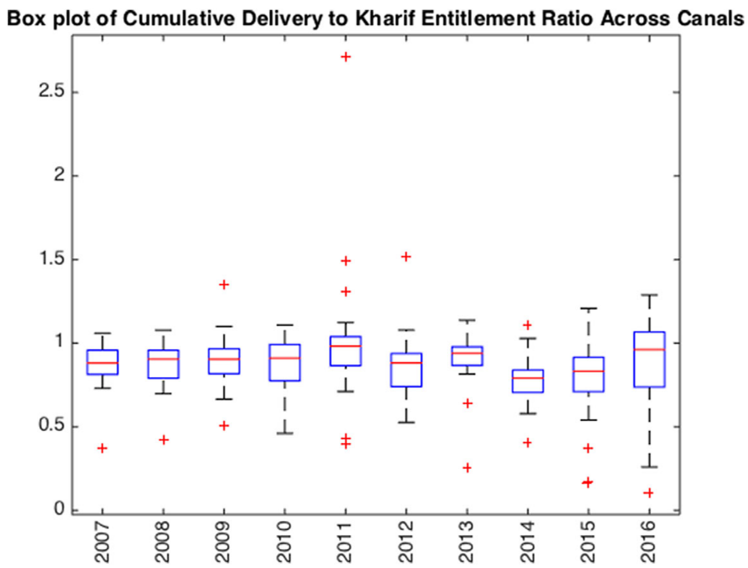


**Figure 7.** Variation in ratio of cumulative delivery to *kharif* entitlements across 25 canals.

Even though the 10-daily flow measurements are at a time-scale that cannot provide a precise assessment of total actual deliveries and deviations in the system, the reported data do capture variations across canals over time, which provides a mesoscale overview of the system. The surface canal distribution system, as evaluated through these two metrics of temporal reliability and spatial uniformity (equity), is not improving in reliability and may even be declining in spatial uniformity trending toward increasing variations. These trends have significant consequences for irrigation agriculture in the region. Recent research on measures to improve production in the region continues to reveal the negative impact of uncertainty in surface irrigation supplies (Mekonnen et al., 2016), and the willingness of farmers to pay higher water prices (e.g., *abiana*) in exchange for increased reliability (Bell et al., 2014).

The differences between entitlements and deliveries result not only from natural variations, e.g., variations in river inflows and rainfall from year to year, but also from a lack of adequate development of forecasting, management, and operational procedures to minimize differences between what is allocated for a canal and what actually gets delivered over the season. A recent study for the Indus River System Authority (IRSA) called for reporting basic gauge data and not the imputed discharge volumes at least until hydraulic studies and formulae are accepted by stakeholders (NESPAK, AHT, & Deltares, Vol. 1, pp. 2–87). In the meantime, emerging technologies for high-frequency measurements, data logging, and dissemination are now paving the way for addressing these issues.

## 4. From Primary to Secondary Channel Flows

Within each of the 25 canal commands in Punjab, 10-daily allocations are translated into a schedule of bulk irrigation delivery commonly known as *warabandi* (meaning "taking turns"). *Wari*s (turns) were documented as traditional practices in early surveys of customary law in the Punjab (Tupper, 1881, Vol. 3, pp. 164ff). The *warabandi* institution aims at ensuring equitable water distribution to farmers through the issuance of irrigation rosters before the start of each cropping season. The rosters assign rotational priorities of water releases in each of the secondary channels (or distributaries) in the canal command. Releases in primary and secondary channels are controlled via manually operated gate structures that deliver water supply to farms via tertiary channels (watercourses or *khala*s). Flow in secondary channels results in a proportional flow in the tertiary channels via outlets that ultimately deliver water to individual farms. The Punjab Irrigation Department currently measures and reports flow on its website at a frequency of one measurement per 24 h for primary and secondary channels. Flow in individual watercourses is not monitored regularly and is inferred from flow in distributaries.

The *warabandi* institution may be understood as the "software" of the system which controls operation of "hardware" comprised of distributaries, gates, watercourses, and outlets. Deviations in execution of the predetermined rotational program for bulk delivery and on-farm individualized delivery are corrected via feedback received from daily flow measurements and a complaint management system by the Program Monitoring and Implementation Unit (PMIU) of the Punjab Irrigation Department. Together, these socio-hydrologic feedbacks form a complex process of monitoring and control of an extensive water distribution system.

### 4.1. Illustrative Example: Hakra Branch Canal Command

The above description may be best understood by an example of how *warabandi* is implemented in one canal command. We focus our attention on the Hakra Branch canal and its distributaries along the Sutlej River in Bahawalnagar district of southern Punjab. This choice has an historical geographic basis. Bahawalnagar and Sutlej canals have had a long history of innovation. In the eighteenth century precolonial period, the region had dozens of inundation canals (Gilmartin, 2015, p. 260). These were improved by the princely state of Bahawalpur and British engineers during the nineteenth century. They included the Eastern Fordwah inundation canal discussed above. In the 1920s, the Nawab of Bahawalpur again worked with the Punjab Irrigation Department on the Sutlej Valley Project that transformed inundation canals including Fordwah and Eastern Sadiqia into perennial canals fed by Sulemanki barrage, constructed between 1922 and 1929 (Michel, 1967). Recall that the Sutlej Valley Project gave rise to downstream concerns in Sindh province, and contributed to formation of the Indus Discharge Commission to carry out scientific flow measurement and data analysis on major rivers in 1921.

As the Indus Waters Treaty (IWT) awarded Sutlej flows entirely to India, a link canal (Balloki-Sulemanki) was constructed in 1967 to carry replacement flows from the western Jhelum and Chenab Rivers into the Sulemanki headworks to supply the Bahawalnagar irrigation division. The Eastern Sadiqia Canal originates on the left bank of the headworks and later bifurcates into two branch canals—the Malik and Hakra Branch Canals. A related reason for selecting the Hakra Branch as a case study is its historical importance for irrigation management research over the past 25 years by the International Water Management Institute and World Bank (e.g., Shah et al., 2016; Waheed-Uz-Zaman et al., 1997; World Bank, 1992).

In this context, the *warabandi* rotational program may be understood as a way to manage the hydrology of limited variable flows in canal commands over the cropping season in the Eastern Sadiqia canal command. It is contingent on timely deliveries in upper levels of the irrigation hierarchy, the variability of which was analyzed in section 3, and link canal flows. In addition, the rotational program has provisions for tackling variability through a clear ordering of priorities. To ensure that the rotational program is implemented in letter and spirit, irrigation managers (farmers and irrigation officials) rely on two forms of feedback mechanisms. First, they rely on daily reporting of flows in primary and secondary channels of the system via manual gauge reading at the heads and tails of each channel. Measured water levels are converted into flows using rating curves. Since the establishment of its PMIU unit in 2006, the Punjab Irrigation Department has published these daily measurements of water levels and flows for all primary and secondary channels of the system on its website. The second type of feedback is a Complaint Management System (CMS) also maintained by the PMIU unit. This may be thought of as the sociological aspect of feedback on the *warabandi* system and other irrigation operations. In some canal commands, feedback is managed by Farmer Organizations, 16 of them in the case of the Hakra Branch that operate under the Bahawalnagar Area Water Board (AWB) established by the Punjab Irrigation and Drainage Authority (PIDA) Act of 1997 (PIDA, 2015). Together, these social and hydrological feedbacks form a complex process of monitoring and controlling the large water distribution system.

### 4.2. Robustness of Rotational Programs Under Daily Measurement

The daily measurement data provided by the Punjab Irrigation Department (PID) are used below to analyze incidents that may be interpreted as exceptions arising in *warabandi* operations. We investigate two types of incidents: *Type 1*: A distributary is assigned the highest priority in the rotational program, but it receives less than 60% of its design discharge; *Type 2*: A distributary is assigned the lowest priority and it receives more than 60% of its design discharge. Note that the occurrence of these incidents is not meant to imply illegal activity or negligence. The number and extent of these first-order incidents are collected to reflect on exceptions from "normal" *warabandi* operations and to conjecture on possible reasons for these exceptions.

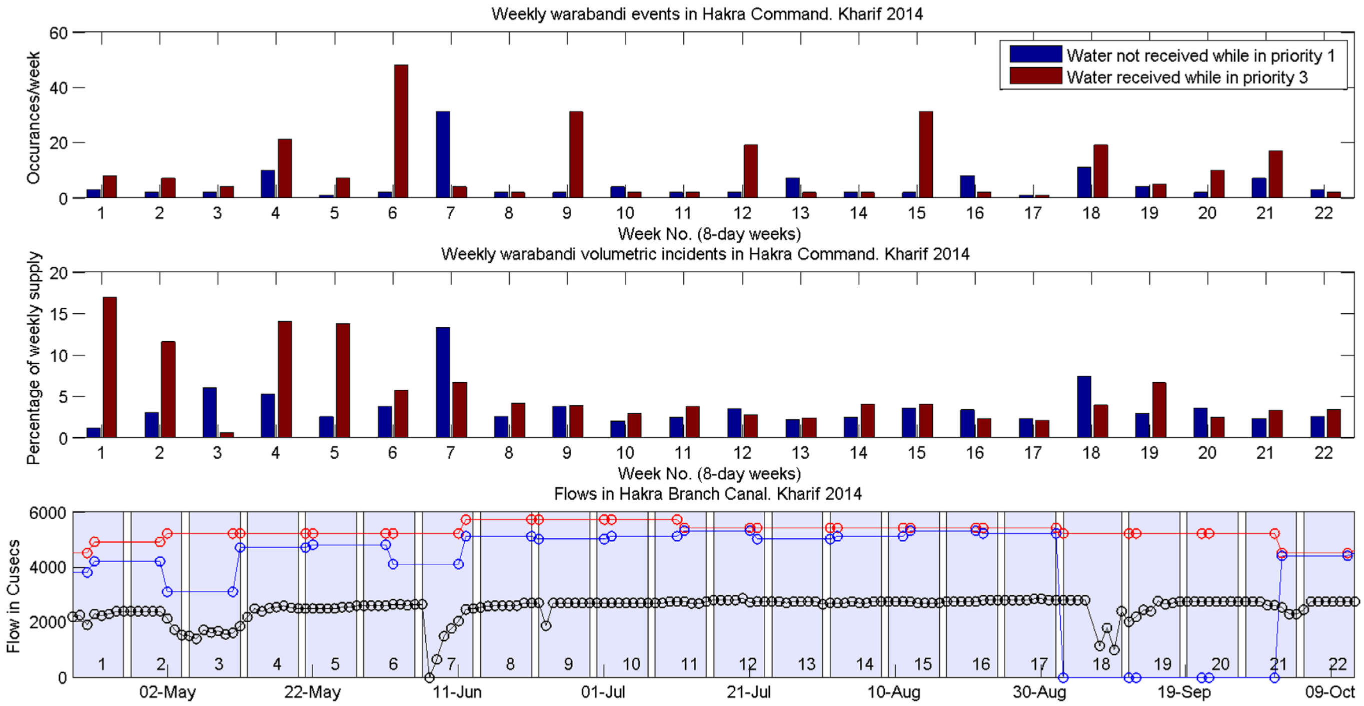


**Figure 8.** Temporal frequencies of *warabandi* incidents in Hakra branch during 22 (8 day) weeks of the *kharif* season in 2014. (top) Number of delivery incidents in top plot; (middle) % volume of those incidents in middle plot; and (bottom) comparison between Eastern Sadiqia entitlements (red), deliveries (blue), and Hakra branch canal flows (black circles).

The results of an algorithmic compilation of these incidents in the *kharif* season of 2014 are given in Figure 8. We aggregate incidents across distributaries temporally in each 8 day rotation period. The top plot in Figure 8 shows temporal variation in terms of the counts of incidents of types 1 and 2. The middle plot displays those incidents as a percentage of total weekly supply. The bottom plot shows how flow variations in the primary channels of the system relate to *warabandi* incidents. Variations in the daily discharge of Hakra branch canal (black circles) are overlaid on *warabandi* periods (numbered 1–22). On the same plot, we plot the 10 daily allocations for the larger Eastern Sadiqia command. Note that the 10 day periods do not align with the 8 day weeks of *warabandi*. More importantly, we also plot the actual deliveries over each 10 day period for Eastern Sadiqia. This helps see how gaps between allocation (red circles) and delivery (blue circles) in weeks 2, 3, and 7 relates to reduced flows in the Hakra branch canal. However, incidents of types 1 and 2 never rise above 17% of total weekly supply during the season, even under sudden collapse of water supply in the primary channels. Overall, one can see that the *warabandi* system, as interpreted using PID daily data, appears to perform quite robustly.

However, this apparent good quality of service contradicts the situation portrayed in both PID's complaint management system and the local AWB reports. Both sources note with concern a rise in incidents of water theft and infrastructure tampering together with a significant drop in the receipt of *abiana* (water tariffs) over the period 2011–2015. This paradox points to the obvious, that until now we have not considered the possibility that the hydrological feedback mechanisms (i.e., PID daily measurements) might be inadequate to capture *warabandi* related incidents. Even more seriously, the daily measurements may be prone to errors and manipulation. We give some high-frequency measurement examples to substantiate that manually collected daily measurements are indeed inadequate to capture the socio-hydrologic dynamics of *warabandi* over a 24 h sampling period.

### 4.3. Rotational Program Under the Lens of High-Frequency Electronic Measurement

The science and practice of monitoring and controlling water resources are undergoing a revolution enabled by new ICT-enabled technologies such as wireless sensor networks, automatic control systems, and remote sensing. Recently, the Indus basin in Punjab has witnessed an interest in piloting real-time flow monitoring systems by both the government and the research community (Ahmad et al., 2013; Muhammad

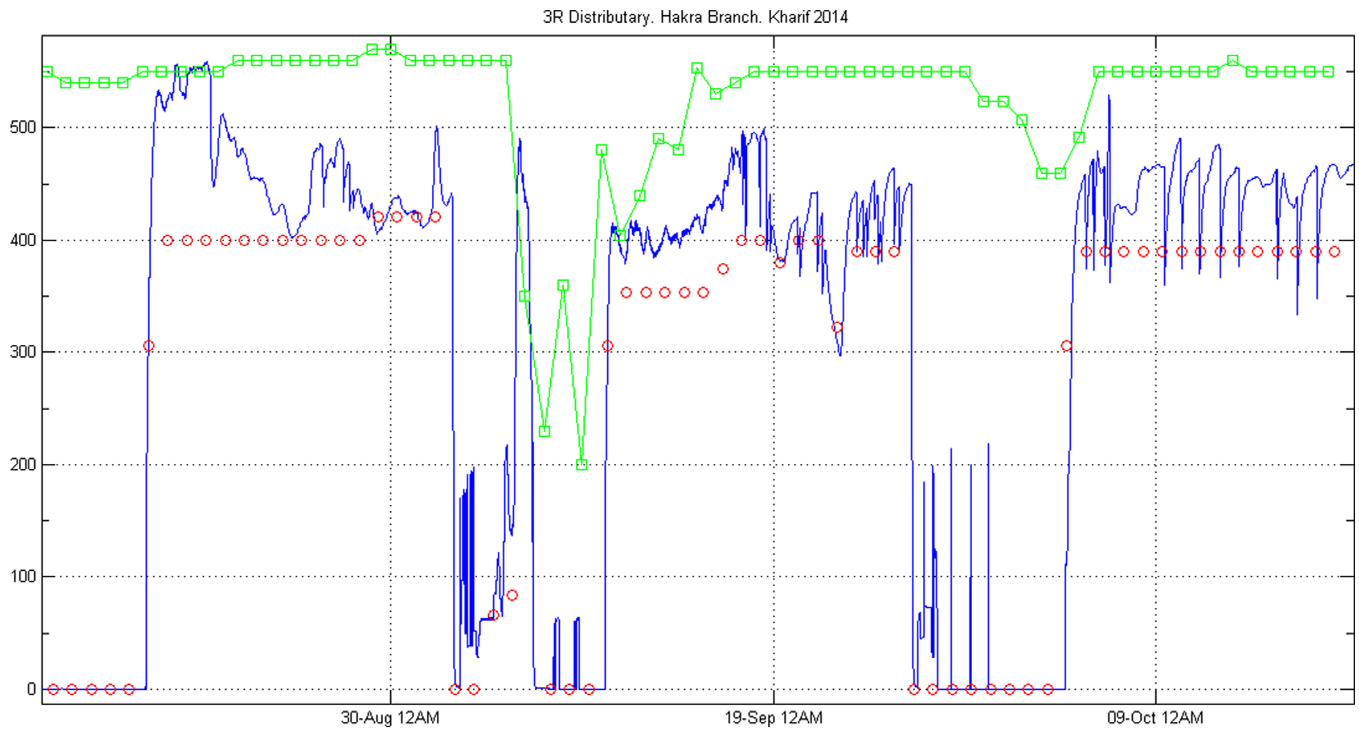


**Figure 9.** High-frequency measurements in a day over a 3 month period. Flows in 3R distributary reported by PID (red circles); high-frequency measurements (blue). Flows in Hakra branch canal (green) are not to scale but plotted to depict relative variation.

et al., 2016). In 2013–2015, all distributaries of the Hakra branch canal were instrumented for real-time electronic measurement and internet-based information dissemination at a 10 min interval for more than one cropping season. While a complete and systematic analysis of the *warabandi* system using these new high-frequency (HF) sensing technologies is beyond the scope of this paper, we provide examples that help explain the apparent contradictions between the social and hydrological feedbacks that are currently in place.

We begin with a chronological commentary on a series of socio-hydrological events in the *kharif* season of 2014 to illustrate how the current reporting system masks significant socio-hydrologic processes in the Indus basin (Figure 9). We focus on Khatan distributary (3R), which in our PID daily measurement analysis emerged as the channel where adherence to *warabandi* rosters was the closest. We focus on weeks 15–22, for which high-frequency and PID daily measurements are compared. We observe the following events unfolding in the Khatan 3R distributary during this period.

*Week 16 (16–23 August 2014)*: 3R is on the highest *warabandi* priority. Supply in 3R is significantly above the measurements reported by PID. The actual flows overshoot the reported flow of 400 cusecs by as much as 140%.

*Week 17 (24–31 August 2014)*: 3R is on medium *warabandi* priority. Supply in 3R is significantly above the measurements reported by PID for the first four days. The flows overshoot the reported flow of 400 cusecs by as much as 125%.

*Week 18 (1–8 September 2014)*: 3R is on the lowest *warabandi* priority. Supply in 3R drops to zero on the first day. During the week, supply in Hakra branch drops suddenly on 3 September. This in turn is due to the sudden gap developed between the 10-daily allocation in Eastern Sadiqia command and the actual delivery.

*6 September 2014*: 3R receives a full supply for 1 day despite being on the lowest priority 3. 3R is not the only channel that receives this short surge of water supply during what looks like an effort to make best use of a collapsing supply in the main. This is the only day in the 182 day PID dataset for *kharif* 2014 when a number channels in the system fail to report their respective daily measurements. Hence, this surge captured by HF sensors does not exist in PID records.

*Week 18 (9–16 September 2014)*: 3R is on highest *warabandi* priority. It receives a full supply, but once again the flows are under-reported. Supply stabilizes to normal in the Hakra Main canal. The reliability gap in the Eastern Sadiqia command level remains high.

*Week 19 (17–24 September 2014)*: 3R is on medium *warabandi* priority. It receives a full supply. Daily flows are no longer under-reported but HF measurements begin to manifest an intraday variation pattern which develops fully in Week 21. Supply is stable in Hakra Main. The reliability gap at E. Sadiqia command level remains high.

*Week 20 (25 September to 2 October 2014)*: 3R is on lowest *warabandi* priority and flow is zero. Supply drops nearly 20% in Hakra Main with no effect on 3R. The gap between allocation and delivery at the Eastern Sadiqia command level is finally closed.

*Week 21 (3–10 October 2014)*: 3R is on highest *warabandi* priority and receives a full supply. Daily PID reporting of flows match with HF measurements at the time of measurement. Below is a typical daily episode as elaborated from Figure 9.

*10 October 2014, 8:00 A.M.*: HF measured flows coincide with the daily measurement time.

*10 October 2014, 8:10 A.M. to 11 October 2014. 7:30 A.M.*: Flow rises to almost 133% of design discharge and is maintained at a high level for this period.

*11 October 2014, 7:40 A.M.*: HF measured flows begin to drop suddenly and rapidly.

*11 October 2014, 7:50 A.M.*: HF measured flows return to the expected flow level.

*11 October 2014, 8:00 A.M.*: HF measured flows coincide with the daily measurement time.

Technically, the PID data does not under-report flows as the daily flow measurements are accurate. However, what happens between the sampling times, and what types of social behavior and channel hydraulics occur during these periodic variations are not captured in the daily PID data.

In summary, one can see that the high-frequency sensor measurements from within the lowest layer of the irrigation hierarchy reveal a wealth of socio-hydrological phenomenon that remain hidden from daily, weekly, and 10-daily aggregations. This new information helps us conclude that the contradictions between social aspects of system monitoring (e.g., in PID's CMS or AWB reports) and the hydrological aspects of reporting may be resolved by use of new technologies that can help inspect and manage the system at the needed spatiotemporal resolutions. This underlines the need for minute-by-minute, inch-by-inch and person-by-person approaches toward understanding socio-hydrology, which may require a drastically new approach toward Indus basin flow management in the twenty-first century.

## 5. Conclusion

This analysis demonstrates how flows are jointly social-and-hydrological in three levels of water channels of the Indus basin of Pakistan. It goes further by presenting this combination of historical geographic and statistical methods as a promising line of research for the emerging field of socio-hydrology. Historical geographic inquiry sheds light on how and why channel flows become measured in different places and times within the basin, while statistical analysis tests expectations about how those flows are allocated and delivered with varying levels of reliability and equity. This approach and insights from the Indus basin bear comparison with other complex river basins such as the Colorado that also have multiple scales of channel flows, measurement, and management (Mustafa, 2013; Sattar et al., 2017).

At the basin scale in Pakistan, we find that river inflow measurements arose in part to address conflicts between Punjab and Sindh provinces in the colonial period. Its importance shifted to measuring international water flows between India and Pakistan, and to national water development planning in Pakistan under the Indus Waters Treaty of 1960. Statistical differences in trends and variability in each of the western and eastern rivers reflect these historical developments, and help define current challenges and concerns for canal irrigation that rely on those river inflows.

Canal irrigation research has a long history in the Punjab dating in modern flow measurement terms to the mid-nineteenth century, with detailed studies of reliability and equity on specific canals. To the best of our knowledge, this is the first system-wide study of canal entitlements and deliveries in the major canals of Punjab province. Analysis of 10-daily flow data was employed to characterize temporal and spatial aspects of reliability and uniformity of supply. Results indicate broad patterns of water deficit in most canals, and limited improvement in performance over the past decade—which call out for further investigation.

Analysis of "surplus" and "deficits" compared canal deliveries with canal entitlements. By improving both the canal entitlement process and the delivery operations process, assessments of deficit and surplus can evolve toward better "meeting of expectations." Ultimately, it is the reliability and consistency of supply that would allow farmers to optimally plan and enhance productivity.

Flows on local distributaries in the Bahawalpur area of southeastern Punjab have a long history of management and analysis dating back to the late-eighteenth century. Conversion from inundation to perennial flows occurred in the early-twentieth century, and new high-frequency measurement, ICT data transfer, and near real-time data analytics promise to transform channel flow research in the early twenty-first century. We show how these technological innovations enable finer-grained temporal and spatial analysis of the performance of traditional *warabandi* system of turns. In addition to system performance, these analytics help address issues of equity and transparency in the system, issues that are at the heart of flow research and management on major canals and rivers as well.

This analysis demonstrates a socio-hydrologic approach that links historical geographic and statistical analysis. The Indus basin in Pakistan also relies on monsoon rainfall and groundwater irrigation, which are constrained by irrigation water quality and socio-economic dynamics, all of which affect and are affected by surface flows. Extensions to these related hydrologic processes and their historical geographic narratives are priorities for future research.

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