Note

Since it was originally submitted, this paper has been carved into two distinct portions, one that looks at allocative efficiency while the other documents farmer adaptations to heterogeneous water availability. Therefore, Part I of this paper is a self-contained paper that studies allocative efficiency of canal water while Part II is a self-contained paper that studies farmer adaptations to canal water availability.

Part I

Agricultural Water Allocation Efficiency in a Developing Country Canal Irrigation System*

Agha Ali Akram†
Yale University

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Abstract

Irrigation systems are critical to agricultural systems in semi-arid parts of the developing world. Although there is ample evidence that canal systems fail to reach their design capacity, there have been surprisingly few studies of the allocation efficiency of water within canal systems. Partly this is due to poor data concerning water withdrawals per farm. This study collects refined measures of water withdrawals and finds evidence supporting the hypothesis that farmers near the head of a canal get more water than farmers near the tail. Accounting for the conveyance efficiency of the canal system ameliorates the efficiency loss somewhat. The analysis builds a strong evidence-based case that water is not allocated efficiently now within the canal. The results suggest that improvements in canal water management or an internal water market would yield efficiency gains for the canal.

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† School of Forestry and Environmental Studies, Yale University, New Haven.
E-mail: agha.akram@yale.edu.

1. Introduction

Irrigation systems power agriculture in large parts of the developing world (e.g. Pakistan, India, Egypt). However, these systems are managed by engineers who are primarily focused on keeping the canal systems working and much less focused on allocation rules within the canal. Farmers in poorly regulated systems therefore have an incentive to keep taking water until the marginal value of water drops to zero (Qaddumi, 2005). There is consequently little water available for farmers at the tail of such systems and the canals service much less land than they were designed to serve (Qaddumi, 2005). The marginal value of the water to farmers at the head is very low while it is very high to the farmers at the tail. This allocation is not efficient and the canal will not reach its potential net value. The fact that most canals actually irrigate less land than they were designed implies that this inefficiency in water allocation may be universal. One study puts the amount of irrigated land lost at close to 5.5 million acres in India and Pakistan between 1994 and 2003 (Mukherjee et al (2010)).

In any case, it is worth examining whether the allocation of water in large irrigation systems is economically efficient. In order to gauge efficiency, we require data on farmer production and water use. The problem is that agricultural production surveys in the developing world tend to have only crude measures of the use of canal water. For example, many studies simply record the number of irrigations that a farmer makes. The amount of water used per irrigation is simply assumed to be the same across farmers. It is consequently difficult to show that farmers are using different amounts of water without a physical measure of surface water used.

This study gathers a unique dataset to analyse the allocative efficiency of surface irrigation water in a large canal irrigation system (the Hakra Branch Canal (HBC)) in Pakistan. The analysis collects actual physical measurements of surface water delivered in-season rather than relying on crude measures of water. Canal water discharge is measured using a flow meter and standard stream measurement protocols during the summer 2012 growing season. GPS measurements capture the precise location of the measurement along the system. It was therefore possible to locate the measurement along the canal system so that the distance from the head to the measurement could be calculated along with expected conveyance losses. The water measurements were followed by a production survey of the farmers at each canal location once the summer growing season was over. The water was consequently measured in season and the production at the end of the season.

Using this dataset, I find that farmer net revenues decline as distance from the head of the canal system increases (see table 1 and figure 1a, 1b and 1c). I also find that the amount of water delivered to farmers declines as distance increases (see table 1 and figure 1a, 1b and 1c). This heterogeneity in farmer net revenue and water delivery suggests that water is not efficiently allocated within the canal. Head and middle farmers are taking too much water relative to tail farmers.

I start my analysis by testing for efficiency in canal irrigation water allocation using traditional measures of water use including turns received, turn time and perceived-depth multiplied by number of turns received. Traditional measures tend to be limited and rely exclusively on farmer recall, reducing their objectivity. The analysis using traditional measures suggests that water allocation is economically efficient and that all farmers receive the same amount of canal water. However, this result is contradicted when more precise volumetric measures of farmer water are used. The volumetric measure of water use suggests head and middle farmers get significantly more water than tail farmers. Even adjusting for conveyance loss, the farmers at the tail get less water. The results imply that water allocation within a canal system remains an important efficiency issue. The problem seems to be an issue for allocation along every reach of the canal.

2. Literature

Much has been written about water in agriculture including an extensive literature in Pakistan. Many of these studies can be classified as irrigation engineering studies such as Latif (2007), Latif and Sarwar (1994), Skogerboe et al (1998), Munir, Kalwij and Brouwer (1999) and Bhutta & van der Velde (1992). These studies typically look at the physical system and/or associated institutional management to either estimate the impact of a given system parameter or the impact of an improvement in that parameter. As an example, Latif and Sarwar (1994) estimate the improvement in water delivery to tertiary canals with changes to the existing irrigation water rotation. Skogerboe et al (1998) estimate channel losses in a selected set of canal reaches.

There have also been theoretical studies of the efficiency of water allocation such as Tsur and Dinar (1997), Tsur (2009) and Chakravorty and Roumasset (1991)) and applied (Berck et al

(1990) and Hurd et al (1999). These studies largely are focused on water allocation within a basin as movement of water between basins is rare because it is so expensive. For example, Hurd et al (1999) develops a spatial equilibrium model that equilibrates basin water supply with the demand functions of users along the basin. The basic insight of these models is that one must equilibrate the marginal value of water within the basin. This yields the highest net value of water across the basin. Water allocation, however, is complicated because there is a difference between water withdrawal and water consumption. For many water users, a substantial fraction of the water withdrawn is returned to the system. The difference between the water withdrawn and the water returned is the water consumed. The basic rule of thumb that emerges is that the marginal value of water consumed is equated across users.

In addition to these theoretical models, there are several examples where these models have been quantified using realistic parameters fit to specific river systems (Hurd et al 1999, 2001). This applied literature tends to be more macro in nature – allocating water to types of users within a basin such as industrial, municipal and agricultural users as well as to broad reaches of the system such as the headwaters versus the mouth of each river system. Additionally, when applied to developing countries, this approach has weak foundations since the underlying demand functions for water are not well understood (in fact, usually a static assumption about price of water is needed and a full demand schedule does not exist) precisely because no micro-level study captures water input in a physical volumetric manner.

The theoretical literature on allocative efficiency within a basin also applies to allocation of water within a canal system. The marginal value of water consumed should be equated across all farmers within the system. If the fraction of water returned is approximately the same across all farmers, the marginal value of water withdrawals should also be equated across farmers within the canal.

However, few studies have applied the economics of water allocation within a canal system. The applied literature has largely assumed that this is already efficient. This study addresses that gap and carefully tests whether water allocation within canals is efficient. One of the handicaps to studying water efficiency within canals is that water withdrawals are measured crudely. In traditional agricultural production surveys, usually done post-season, farmers are asked about their water use. This can range from very basic binary measures of yes or no to whether they irrigate to slightly better measures about the acreage under irrigation to the "best" available measures which include number of irrigations, length of each irrigation and the perceived depth of each irrigation. Although the measure is adequate for determining the farmer relied on irrigation water, it may not be precise enough to differentiate the water used by one farmer versus another. In order to address this source of measurement error, this study goes beyond using the traditional measures of water withdrawal once the season is completed and instead actually measures water flows along tertiary canals during the season. This yields much more precise measure of the water actually withdrawn by each farmer along different tertiary canals. The study compares the allocation of water across farmers using both traditional measures and these more precise in-season volumetric measures.

3. Theory

The theory is a classic economic problem. The purpose is to allocate a given amount of water, $\overline{W}$, (the quantity withdrawn by the canal system) to the myriad of farmers within the canal. The objective is to maximize the total benefit of the water across the canal. That is the objective is to maximize the sum of the benefits across all the farmers within the canal given that the canal system has a fixed amount of total water,

$$\begin{gathered} \max_{v_1, v_2} \{B_1(w_1) + B_2(w_2)\} \\ subject\ to, \\ \sum_i w_i \leq \overline{W} \\ 0 \leq w_i \leq \overline{W}, \qquad i = 1, 2 \end{gathered} \tag{1}$$

Where B_i is a single-valued globally concave net benefit function for consumer i; w_i is the water received by a farmer and $\overline{W}$ is the total surface water endowment. B_i is twice differentiable ($B_i{}' \geq 0, B_i{}'' \leq 0$). In this initial analysis, we do not account for groundwater withdrawals or return flows. We assume that the returns are proportional to water withdrawn and that groundwater withdrawals have the same price for every farmer. That is, they face the same marginal cost to pump the water from below ground. One can therefore focus on the efficiency of surface withdrawals within the canal. Assuming an interior solution, the first order conditions are,

$$\frac{\partial B_1(w_1)}{\partial w_1} = \frac{\partial B_2(w_2)}{g\partial w_2 g} \qquad (2)$$

A complication one can add to this model is that there is a conveyance loss that increases with distance within the canal. This reflects surface water that leaks from the canals system itself as water flows within it. This implies that one needs more water allocated at the head of the canal to deliver a fixed amount of water to a farmer the more distant that farmer is from the head. Taking into account conveyance loss changes the objective slightly. The water received by each farmer is only a fraction of the water sent to that farmer. Presumably, the fraction decreases with the distance the water must travel to get to the farmer. The rate at which the water decreases (the conveyance loss) with distance may vary amongst reaches of the canal as some reaches may be lined or well maintained to reduce conveyance loss relative to other reaches. The new objective is to maximize the sum of net benefits across all farmers taking into account the fixed quantity of water and the conveyance loss:

$$\begin{gathered} \max_{v_1,v_2}\{B_1(w_1) + B_2(w_2)\} \\ subject\ to, \\ w_i = z_i v_i, \qquad \sum_i v_i \leq \bar{W} \\ 0 \leq z_i \leq 1, \qquad 0 \leq v_i \leq \bar{W}, \qquad i = 1, 2 \end{gathered} \qquad (3)$$

Water received, w_i, is what the farmer actually gets while the water that is sent to the farmer is v_i. The fraction that the farmer gets, z_i, is a function of the distance from the head of the canal. This fraction depends on how well the canal conveys the water within it. It depends upon how much water is lost, z_i, an exogenously set efficiency term that measures effective water transported to a given location, and v_i, which is the initial surface water sent towards the farmer. For effective water transported, the greater the delivery efficiency i.e. greater value of z_i, or the larger the amount of water allocated i.e. v_i, effective water delivered increases. The model takes into account the water lost within the canal system from leakage and evaporation. Let us call $z_i v_i$ the effective water delivered. First order conditions result in the following efficiency condition,

$$\frac{\partial B_1(w_1)}{\partial w_1} z_1 = \frac{\partial B_2(w_2)}{\partial w_2} z_2 \qquad (4)$$

This condition states that the marginal benefit of allocated water be equated across farmers with adjustments made for water delivery efficiency (Chakravorty & Roumasset (1991)).

4. Data

4.1. Context

The following is drawn from Akram (2013). The Indus Basin Irrigation System (IBIS) is a continuous-flow, fixed-rotation system with a significant network of infrastructure regulated by two major multi-purpose storage reservoirs: Mangla and Tarbela, a series of barrages, inter-river link canals, 45 major irrigation canal commands and over 120,000 watercourses delivering water to farms (Yu et al, 2013). Figure 2a shows a (grossly) simplified representation of the entire system with head waters located in the Himalayas and final exit into the Arabian Sea, with canal commands along the way.

Each of the 45 main canal commands (or canal systems) can be broken down into three distinct levels: (1) primary or main canals; (2) secondary canals or water channels (also referred to as distributaries and minors); and (3) tertiary canals or watercourses. The structures mediating discharge between canal commands and, within them, between primary and secondary canals are adjustable in nature, i.e. they tend to be gates that can control discharge. An outlet is the point at which water from a secondary canal is transferred to a tertiary canal.

The current management of the system has two tiers separated at the outlet structure (i.e. where the secondary and tertiary canals meet). The first tier is essentially controlled by government institutions and runs all the way down to the control of discharge between distributaries (secondary canals). However, as a result of recent reforms, Farmer Organizations (FOs) sometimes play a role water distribution at the distributory level. The second tier is farmer managed at the watercourse level (tertiary canals). See figure 2b to get a sense for the tiered nature of the irrigation system. At the highest level, the Indus River System Authority (IRSA) manages and allocates water to the four provincial irrigation departments. The irrigation department in each province, known as the Provincial Irrigation and Drainage Authority(PIDA), prepares a Provincial Irrigation Demand (PID) on a 10-day basis for IRSA, which is responsible for making releases from the three major reservoirs based on projected demands(Tarbela, Mangla and Chashma) (National Water Policy, 2004). Once IRSA allocates water, the PIDA assumes responsibility for distributing that water internally within the canal commands under its jurisdiction. PIDA supplies canal water to farmers, and it manages, operates and maintains the entire irrigation network, except the tertiary canals that farmers maintain (Latif, 2007). Although the Provincial Irrigation Department prices water, this price bears no relation to the actual market price of water (or the actual quantity of water delivered). At the tertiary (watercourse) level, the system of water allocation in Pakistan is called *warabandi*, literally translated as “turns” (wahr) which are fixed (bandi). The warabandi system consists of a continuous rotation of water in a cycle lasting 7-10.5 days; each farmer in the watercourse will receive water once for a fixed time during each cycle (Bandaragoda, 1998). This cycle starts at the head of a watercourse and progresses to the tail, and during an allotted time-segment within a cycle a farmer has the right to use all of the water flowing in the watercourse.

4.2. Data

Surveys of farmers on canal irrigation systems are able to capture the use of most inputs reasonably well (e.g. bags of fertilizer, litres of fuel etc). The one input that is usually not captured very well is canal irrigation water. To counter this, proxy measures for water availability are used such as number of irrigations applied or perceived depth of a typical irrigation. However, these measurements tend to be rough; e.g. perceived depth applied is very dependent on a farmer’s recall, his interpretation of depth as a measure and the assumption that water actually ponds in his fields so that a depth is in fact observable.

The data set I use for this study is unique. In particular, two features set it apart from most other agriculture and irrigation datasets. The first feature is collection of in-season water discharge data. Many agricultural surveys tend to gather either crude measures of irrigation such as the amount of land irrigated or then collect farmer perception data such as perceived depth of irrigation applied (which, incidentally, is likely endogenous since depth perceived may be affected by the amount of land a farmer plants). I selected three distributaries along the Hakra Branch Canal – namely 3R, 6R and 9R (the ‘R’ stand for right-bank of the canal) – from which I then proceeded to select and measure discharge in watercourse outlets. I measured discharge in as many watercourses as I could along the distributory. This was somewhat opportunistic but I was able to measure discharge in at least two-thirds (if not more) of all watercourses on the primary distributory trunk for all three distributaries. The measurement of discharge followed standard stream measurement protocol where the stream was divided into cross-sectional segments and flow was recorded in each segment separately. Flow was measured using a flow meter. The total process took 12 days from start to end and included one measurement of discharge per outlet selected. As might be apparent, this is a snapshot and not a season level measurement. If we assume that discharge across the outlets measured is proportional, then this snapshot provides a good guide for relative discharge levels. The season level water volume calculation may not be very accurate but certainly we will know where outlets stand in comparison to each other in terms of discharge.

The second unique feature of this data set is a relatively precise measure of distance along the canal system. Typically, it is crudely measured, where farmers are lumped into the head, middle or tail of a canal segment. If a survey is able to collect distance, it typically relies on a farmer's report of the distance. This may not be entirely reliable as farmers may not be keenly aware of all distance measures that lead up to their plot. In the case of this study, there are three distinct distance components (as shown in figure 2b) – a primary distance, a secondary distance and tertiary distance. Primary distances can be had from public records but secondary and tertiary distances must either be measured or sought from farmers. Public records of secondary distances, i.e. distance from the head of the secondary canal up to an outlet structure on which a farmer's plot may be found do exist, but the naming scheme is different to that on the ground. Thus, based on my own field experience, a farmer may know that he is on a given outlet structure but the public record will only speak to an outlet's distance from the head (the public record does not associated the distance measure with the outlet structure number). Thus, one must rely on the farmer's report of the distance from the head of the system, which may or may not be correct (farmers are keenly aware of their tertiary distance i.e. distance from the head of the watercourse but their knowledge of the exact distance from the head of the distributory can be patchy). I used a GPS device to locate each point that I made water measurements at. This meant I could plot these points in a GIS file and carefully (to within a few feet) place an outlet structure along the canal (outlet structures are the points where I made water discharge measurements). I used ArcGIS which has a basic satellite image available of the Earth as a background. Using a combination of my GPS points and the available ArcGIS satellite image, I was not only able to trace out the irrigation system I was studying but also locate outlets on it. Thus, I could calculate (using ArcGIS) the distance from the head of the canal system to any given outlet structure along a distributory. This also meant that I could direct the survey team that did the post-harvest survey to survey farmers at specific locations.

A full production survey was conducted after the summer 2012 growing season (locally called *Kharif*). I collected production data from farmers along select distributaries (3R, 6R and 9R). Data was collected on output by plot crop and input by plot crop. Special interest was paid to the collection of surface irrigation water use and groundwater use. For surface water use, we asked farmers about the number of turns they got, the turn time and also their perceived depth of water applied. Calculating groundwater use requires the collection of data on pump age, power and depth of the bore. Along with this, we also asked farmers basic socio-economic questions to act as possible controls.

This, two step (asynchronous) data collection posed a challenge. Typically, production data for a season is collected once the season is over, since all outcomes have been realized. But I measured discharge in-season, which meant that I had to then locate farmers post-season on the watercourses I measured discharge on. This meant that I had to work closely with local irrigation officials to make sure I was able to record the correct name of a given watercourse (this is important – public records state only distances not watercourse names). Watercourse names are critical as they allow one to associate a watercourse with a village. The issue that then emerges is a logistical one involving off-road travel and locating farmers who I intended to survey that reside in villages (not at the head of a watercourse where I made my volumetric measurements). Thus, watercourses then had to be associated to villages – which is why I made sure I collected watercourse names at the time of discharge measurement. Once the universe of villages was discovered, I could dispatch my survey team to randomly sample within a village (the criteria to be a valid survey respondent was to be a farmer on the watercourse in my list).

As stated, one of the key variables of interest (and one that differentiates this dataset) is surface water volume used by farmers over the course of the growing season. I collected three crucial pieces of information that help construct this measure: the amount of time a farmer kept his farm gate open at each turn (time per turn), how many turns he received in the growing season (turns) and finally watercourse discharge (volume per unit time). Then, to get season level water volume delivery to a given farmer, I multiply these three components. Note that all three components are objective in that farmers turn times are set externally as are the number of turns received. Discharge of course is an objectively measured number. Thus, our measurement of this important exogenous phenomenon is does not rely on farmer perception in any way.

4.3. Identification

Given the simple theory set up earlier, one way to test for allocative efficiency is to estimate a concave form for the relation between farmer profits and water received (both normalized by area). In this cross-sectional dataset farmers are exposed to heterogeneous water delivery and if a concave profit function is estimated it implies that in fact farmers are located on different points along the concave profit surface; see figure 5. Thus, by estimating a concave relation between farmer profits and surface irrigation system water delivery, we should be able to test efficiency. Underlying this is the key assumption that canal water delivery to farmers is exogenous. This is a safe assumption since water delivery is set externally to farmer choice and also the total volume delivered in a season varies, depending on factors such as snow-melt in the Himalayas. In terms of the system's structure, if there is discharge in primary canals then there is discharge in secondary and tertiary canals. The structures at the lower levels of the system are static and not amenable to alteration. Within a tertiary canal, farmers open their gates for predetermined (based on a non-market non-negotiable time table created decades ago) periods of time to access discharge in the canal. Thus, within a tertiary canal, farmers have a distinct incentive to ensure that everyone adheres to the schedule lest someone take more than their allotted share. It should be noted that 90% of the sample is utilising groundwater which implies that the surface water constraint is binding (hence the need to supplement with groundwater).

4.4. Summary Statistics

Table 2 provides some summary statistics. Our complete sample contains 363 farmers. The average farmer in our sample has had 28 years of experience in agriculture, owns the primary plot of land he cultivates which is worth about Rs. 6.2 million.

4.5. Conveyance Efficiency

It is important as we enrich the model to, as a first step, include CE. Again, what I want to estimate is the volume of water lost on a unit as it makes its way from the blue dot to the red dot in figure 2b. That means each unit of water must be scaled up to its pre-delivery or at-source volume. In order to calculate CE we can use knowledge about and features of the HBC's physical structure and existing work. As a reminder, there are three levels to the HBC (primary canals, secondary canals and tertiary canals) and as shown in figure 2b, a farmer is located at the end of a primary, secondary and tertiary canal. Thus the water received by a farmer must be adjusted upward for the distance it travels along primary, secondary and tertiary canal segments. The secondary canal segments required the use of two different approaches to estimating CE and yielded 4 different CE estimates. Therefore, going forward, when I make adjustments to water received by farmers, I will use each of these four different estimates. The procedure used to scale water upward has been described in the appendix.

5. Results

5.1. Traditional Measures of Water Use

I start my analysis by testing allocative efficiency using traditional measures of water use by farmers i.e. those that are gathered post-season in the production survey and include turns received, turn time and (depth x turns received). To test for allocative efficiency, I will use a second order polynomial in farmer surface water use and relate that to farmer net revenues,

$$\pi_i = \alpha + \beta_1 m_i + \beta_2 m_i^2 + \boldsymbol{X_i \gamma} + \varepsilon_i \quad (5)$$

Where π_i represent normalized farmer net revenues, m_i and m_i^2 are traditional measures of surface water delivered and its square while $\boldsymbol{X_i}$ is a vector of controls. The results of this specification are shown in table 3a. The results seem not to show much of anything – neither the linear term nor the quadratic term have any significance though have positive coefficients. A positive coefficient on the quadratic actually implies convexity. This could be interpreted as efficiency in allocation, since marginal net revenues are equal across farmers.

Another specification I use is more generous to the idea of non-linearity and uses a linear spline. I run specification (5) using a simple two-part spline. It could be that the second-order polynomial is restrictive and what is needed instead is a piece-wise function. I use a two-part spline, with a knot at the median farmer's water use and at the 50^{th} percentile of water use (traditional water measures). Thus, the equation estimated is of the form,

$$\pi_i = \alpha + \beta_1 m_{1i} + \beta_2 m_{2i} + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{6}$$

Where the numbered subscript on the water measure, i.e. m_{1i} and m_{2i}, indicates the first and second spline segments. The results are shown in table 3b. Specifications (1), (3) and (5) use the median farmer as the knot while (2), (4) and (6) use the 50th percentile of the range. Again, it is quite clear that traditional measures are not able to pick up any concavity. These measures either imply that allocation is in fact efficient (constant marginal net revenues) or, in the case of specifications (2), (3) and (6), imply convexity (though the coefficients are not precise).

5.2. Volumetric Measure of Water Use

I now use my improved volumetric measure of water use calculated for each farmer using in-season measures of discharge. As with the traditional measures of water use I start with a second order polynomial specification,

$$\pi_i = \alpha + \beta_1 w_i + \beta_2 w_i^2 + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{7}$$

Where π_i represent normalized farmer net revenues, w_i and w_i^2 are volumetric measures of surface water delivered and its square while $\boldsymbol{X_i}$ is a vector of controls. The results are shown in table 4 (specifications (1) and (2)). The results are striking and contradict earlier results that used traditional measures of water use. The results strongly suggest concavity which implies that water delivery is inefficient (since by implication the marginal net value of farmers is different), i.e. water allocation is not efficient and that there are farmers at different points along the response surface (the profit function surface). Figure 6a visually captures the form of the relation estimated.

Next, I use a spline to characterize the relation between farmer profits and measured water use,

$$\pi_i = \alpha + \beta_1 w_{1i} + \beta_2 w_{2i} + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{8}$$

The results of are presented in table 4. As before, the numbered subscript on the water measure, i.e. w_{1i} and w_{2i}, indicates the first and second spline segments. Specification (3) uses the median farmer as the knot while (4) uses the 50th percentile of the range. As with the polynomial, there is a strongly concave relation indicated by the estimation results which adds to the evidence of inefficient allocation.

5.3. Adjusting for Conveyance Efficiency

As was discussed, we can enrich the analysis by adjusting water delivered for canal system delivery efficiency or conveyance efficiency (CE). The simple test of non-linearity no longer works, since the amount of water at source is not necessarily equated (i.e. if I scale up water delivered by the amount lost in transit based on the CE relationship derived earlier and run a similar specification to (7), detecting a concave form will be a false result). Instead, we must be truer to the actual efficiency condition stated in equation (4) and scale marginal net revenues derived in (7) by CE (there are four different CE calculations). Then, regressing these adjusted marginal net revenue values on actual canal water deliveries should indicate whether there is inefficiency in allocation (a significant coefficient on this simple linear form will imply inefficiency). Thus, the form of the estimated equation is,

$$\mu_i^{CE_j} = \alpha + \beta_1 w_i + \varepsilon_i \qquad (9)$$

Where $\mu_i^{CE_j} = \left(\frac{\partial \pi}{\partial w_i}\right).CE_j$ i.e. it is the marginal net revenue estimate from equation (7) with CE adjustment factor j applied to it and w_i is a volumetric measure of surface water delivered. No other components are included in the equation since this is a marginal revenue equation. The results of this specification are shown in table 4b. Specifications (1) – (4) apply different CE adjustments to the marginal net revenues calculated using specification (7) i.e. the dependent variable in each specification is adjusted using one of the four CE factors. As reference for the coefficient estimated, consult specification (2) in table 4a for the unadjusted case (the reference value for the constant is 2280 and reference value for the slope coefficient is -66.81 per unit of water delivered). As expected, the coefficient on w_i is negative and more importantly it is significant. The fact that it is significant implies that even with CE adjustment, marginal net revenues are not being equated across farmers.

5.4. Discussion

5.4.1. Control Variables

It is worth briefly looking at the role of control variables. Table 4a' reports the coefficients of the control variables from table 4 specification (2). Included in each regression is a set of control variables that include farmer socio-economic data and a measure of local groundwater quality. These are just correlations but two are striking. Farmers that responded affirmatively to "Number of household members that work?" and "Are you involved in livestock production?" tended to see higher net revenues. The former could be a case of lower reliance on outside labour, thus reducing direct expenditures (though the question asked more broadly about the number of household members that work; presumably, at least some of the work that household members do is on-farm). The latter might suggest a farmer adaptation to changes in water availability and quality (both canal and groundwater; farmer adaptations have been explored in a companion paper). Both deserve further exploration.

Groundwater quality is measured as electrical conductivity (EC) in siemens per meter. Higher conductivity indicates the presence of more minerals and salts. This also means that a higher EC value implies poorer quality water. This variable is exogenous thus its effect on farmer net revenues can be seen as causal. As with canal water delivered, a second order polynomial in groundwater quality was used in all regression specifications. The relation implied is concave. This is seemingly strange – it seems more reasonable to imagine a declining relation between the two i.e. higher EC leads to lower net revenues. This requires further exploration but it could have to do with the farmers mixing surface and groundwater.

5.4.2. Improved Measurement and Inefficiency in Allocation

It is quite apparent from the results that: (1) traditional measures of water use by farmers misleadingly indicate that allocation is efficient; and (2) with an improved measure of water use, water allocation is inefficient (even when adjusted for CE). One important question that arises is how this inefficiency plays out spatially. Specifically, how do the marginal net revenues of farmers at different locations on the canal system compare? In order to answer this question, we must first find out how much water farmers receive at different points along the canal system. I am able to find this out at the primary and secondary channel level by splitting them up into head, middle and tail segments (where each is a third of the distance along the primary or secondary channel level). A distinct pattern in the marginal net revenue of water and location on the canal system emerges. Table 5a shows average water delivery by primary canal location and table 5b shows average water delivery by secondary canal location. Specification (1) in both tables regresses an unadjusted canal water delivery i.e. unadjusted for conveyance losses. Specifications (2) – (5) regress adjusted canal water delivered. Generally, the head and middle segments of the canal tend to get the same amount of water per farmer while the tail tends to get significantly less. Both tables show that the coefficients on the head indicator are negative but only for some specifications are they significant. The tail tends to get significantly less than the head and middle segments in all specifications across both tables.

With these estimates I am able to compare marginal net revenues by location – with the typical location specific canal water delivery, a location specific marginal net revenue can be had. This has been visually represented in figure 7 (both unadjusted and adjusted water deliveries are shown). Dotted lines represent average water delivery to head segment farmers, solid lines represent average water delivery to middle segment farmers and dashed lines represent average water delivery to tail segment farmers. Blue lines refer to primary canal head, middle and tail while red lines refer to secondary canal head, middle and tail segments. As can be seen, the head and middle segments receive equal quantities of water (the dotted and solid lines appear to overlap). Marginal net revenue values for each case (primary and secondary segments with and without CE adjustment) are reported in table 6a and 6b. What is evident from figure 7 and table 6a and 6b is that the middle segment invariably has the lowest marginal net revenue while the tail has the highest marginal net revenue from canal water. Additionally, across the primary canal segments, the head and tail tend to have higher marginal net revenue from water. Across the secondary canal segments, the head and middle have the same marginal net revenue which is lower than the tail’s.

5.4.3. Adjusting for CE

How do the estimates without adjustment for canal losses compare to estimates with adjustment (i.e. the estimates in table 4a and 4b)? A simple way to compare the two sets of estimates (unadjusted vs. adjusted) is to run a simple test of difference in the marginal net revenue by farmer i.e. the difference in the average marginal net revenue across the two distributions generated by the unadjusted and adjusted estimations. The results of this test are presented in table 7. The results of this test indicate that the marginal net revenue implied with an unadjusted measure of water use is consistently higher than the marginal net revenue implied with a water measure adjusted for CE by about PKR. 700. In a sense, the inefficiency is ameliorated somewhat with this adjustment. In fact, figure 7 also makes this quite apparent as the farmer with the highest and lowest marginal net revenues tend to have less of a difference with the CE adjustment made (red, green, yellow and grey lines) as compared to when there is no CE adjustment made (blue line).

5.4.3. Welfare Gain

With the analysis conducted we are in a position to calculate changes in welfare if we improve allocation to an economically efficient one. One simple way of calculating this change is to: (1) calculate total net revenue as it stands for the entire system given the existing allocation; (2) calculate the total net revenue for the entire system with an optimal allocation. An optimal allocation would be equal water for each farmer at point of use and point of origin assuming no losses in the canal system and point of origin assuming losses in the canal system. The results are shown in table 8 and really drive home the degree of inefficiency. Each row shows a before and after comparison (existing vs. efficient) of allocation. The first row does a simple comparison without adjustment to canal water (i.e. does not account for canal losses). Thus, the allocation made at the head of the system is assumed to remain true at the points of consumption (no loss in volume in transport). This is a very straightforward calculation since it requires only that water is equated across users. The result is striking – with improved allocation, welfare is improved by 14%. With the adjustments for loss, the results are essentially unchanged. The gain in re-allocation is about 13%.

It should be said that this is not representative of the HBC system nor the broader canal system in Pakistan. The sampling was not designed to representatively capture farmers at different levels of water allocation across the HBC. So, the above conclusion is only true for this sample. However, it is still a very striking result.

6. Conclusions

It is quite apparent that the relationship is linear when we do not use improved measures of water use by farmers which wrongly implies that farmers have constant marginal net benefits from surface water. Using an improved in-season volumetric measure of water use by farmers contradicts the results of estimates that use traditional water use measures. Volumetric measurements of farmer water use clearly show inefficient allocation. A simple adjustment, based on sound theory and good measurement, of the volumetric measure of farmers' water use nuances this core result of inefficient allocation – namely, adjusting for canal losses indicates that the inefficiency is in fact not as great as a first cut estimation would suggest. Thus, improving measurement and guiding the analysis with simple but sound theory takes us from not detecting inefficiency to detecting inefficiency in water allocation; and from detecting inefficiency in water allocation to finally concluding that in fact the inefficiency is not as severe as a first cut analysis would suggest. Additionally, it was found that there was a distinct spatial pattern to the allocative inefficiency, where it was found that the tail farmers invariably had the highest marginal net revenue from canal water while middle segment farmers had the lowest marginal net revenues. Interestingly, at the primary level head segment farmers had marginal net revenues that tended to lie between middle and tail segment farmers while at the secondary canal level head segment farmers had marginal net revenues that were indistinguishable from middle segment farmer's marginal net revenues.

It is clear that there are substantial welfare gains (in the order of 12% – 14%) to be had with efficient allocation. This is true whether conveyance efficiency is accounted for or not. Regardless, this study provides for the first time a solid empirical foundation for the need for a water market.

What the study is not able to do is determine the welfare gains (if any) when groundwater is accounted for – surface water is not completely lost since canal seepage is later pumped out by farmers. The theory can in fact be further enriched with groundwater use. I do have measurements of groundwater use and local groundwater quality and depth. Thus, including groundwater in my analysis is next on the research agenda. Including groundwater in theory complicates the efficiency conditions and also increases the data requirements. But it is a very worthwhile direction to take, since including it may once again swing the results of the test for efficient allocation.

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Figure 1a.
Canal water and net revenue trends over secondary canal distances.

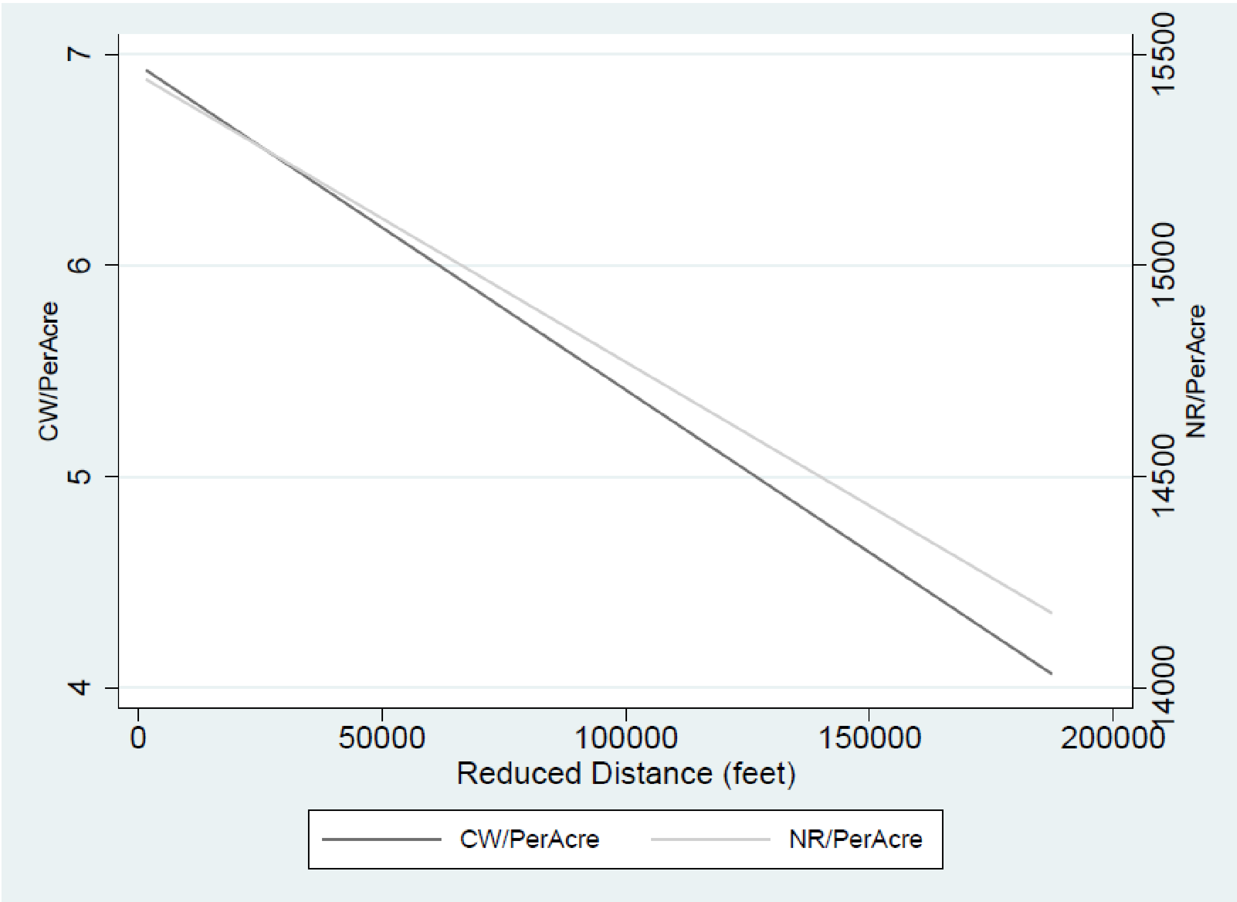


Figure 1b.
Canal water and net revenue trends over tertiary canal distances.

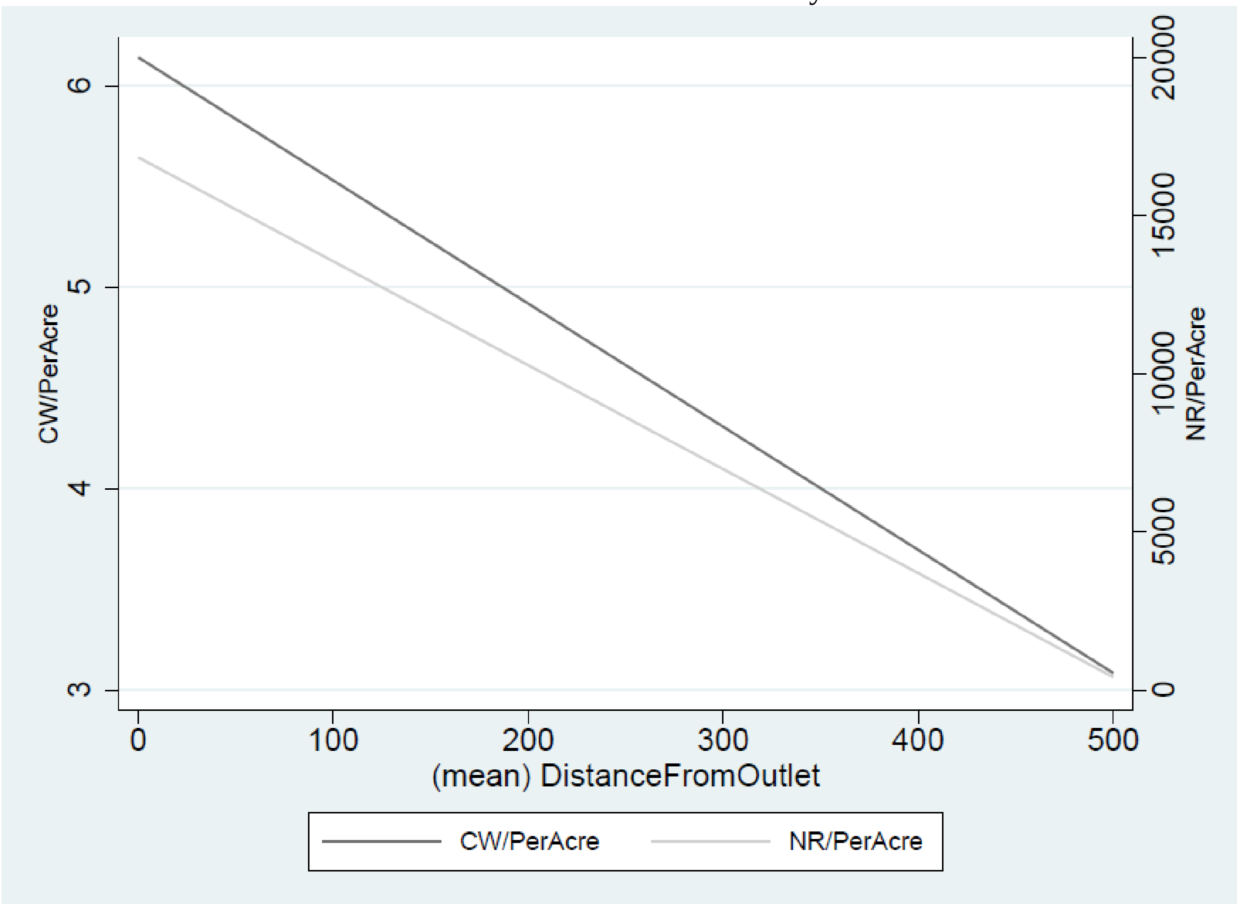


Figure 1c.

Canal water and net revenue trends over total canal distances (i.e. primary, secondary and tertiary canal distances).

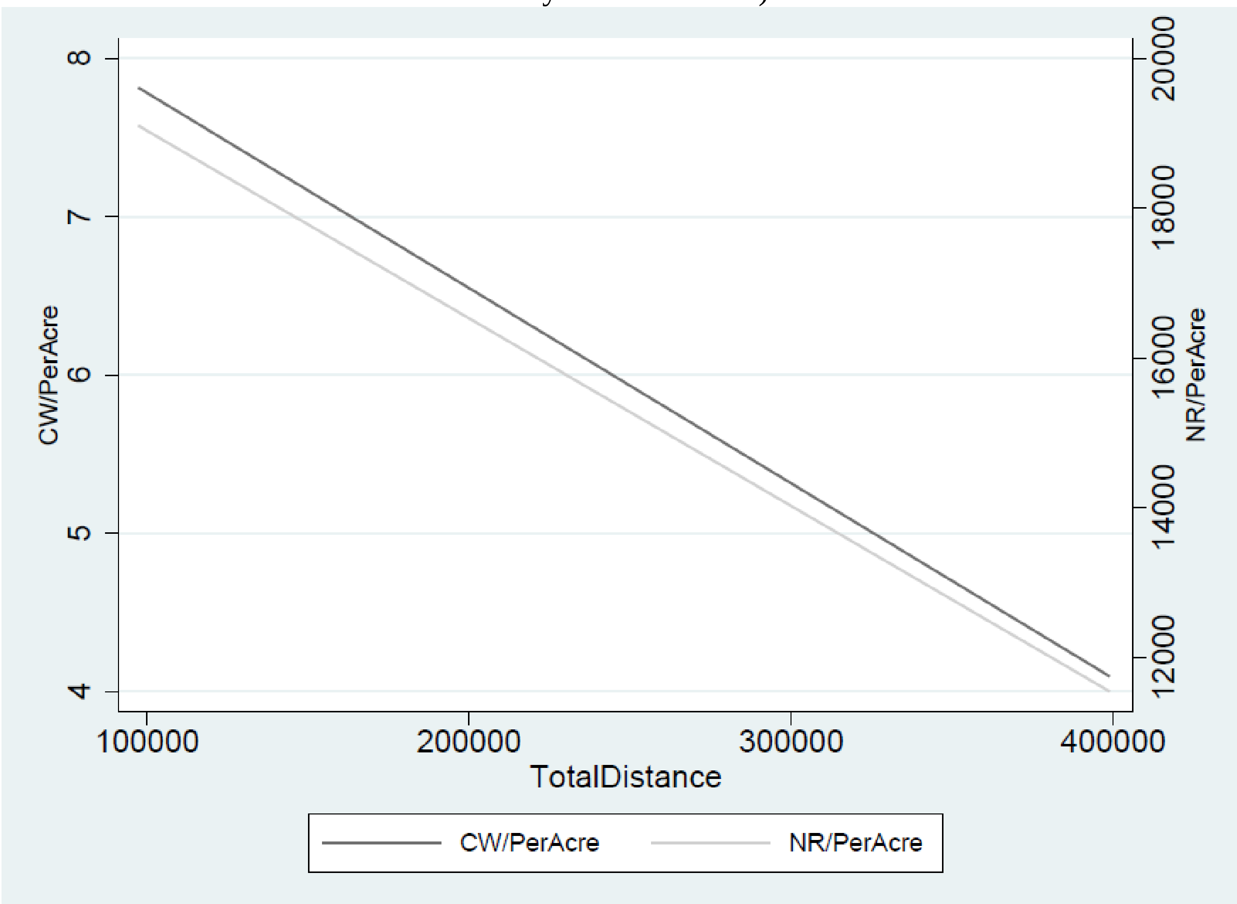


Figure 2a.
A simplified schematic of the Indus Basin Irrigation system

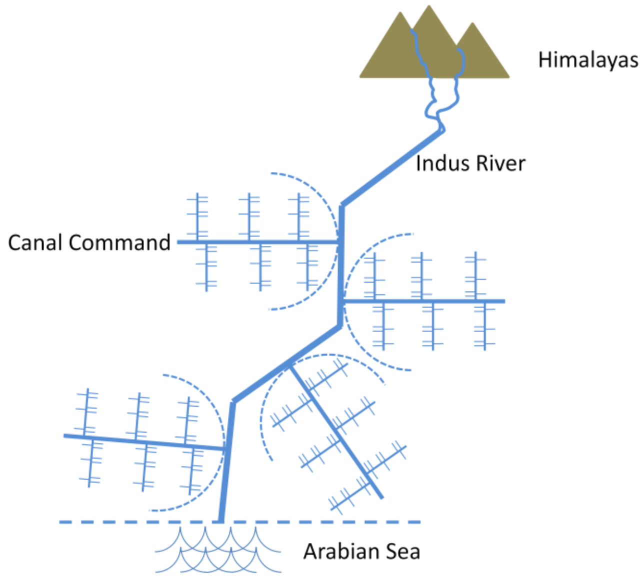


Figure 2b.
A simplified diagram of the three levels of a canal command. Blue arrow shows path water takes to get to farmer (red dot) from source (blue dot).

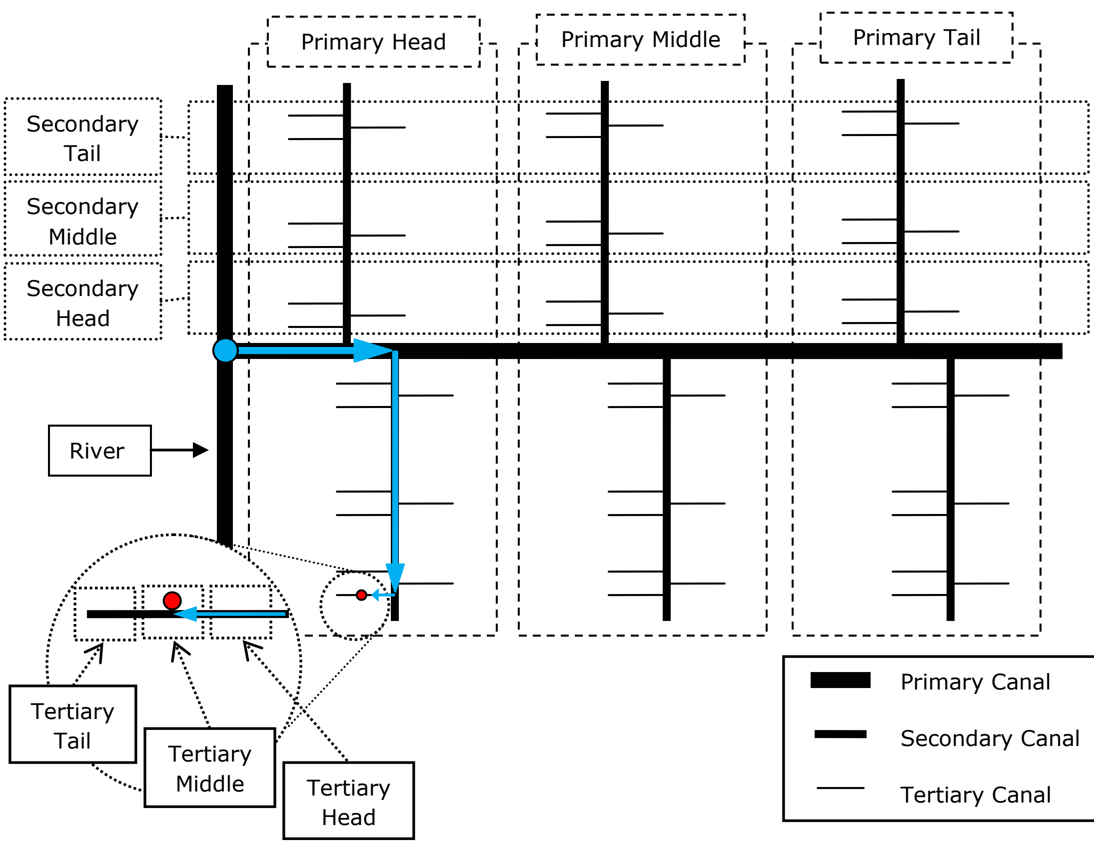


Figure 3a.
A simplified schematic diagram of the Hakra Branch Canal.

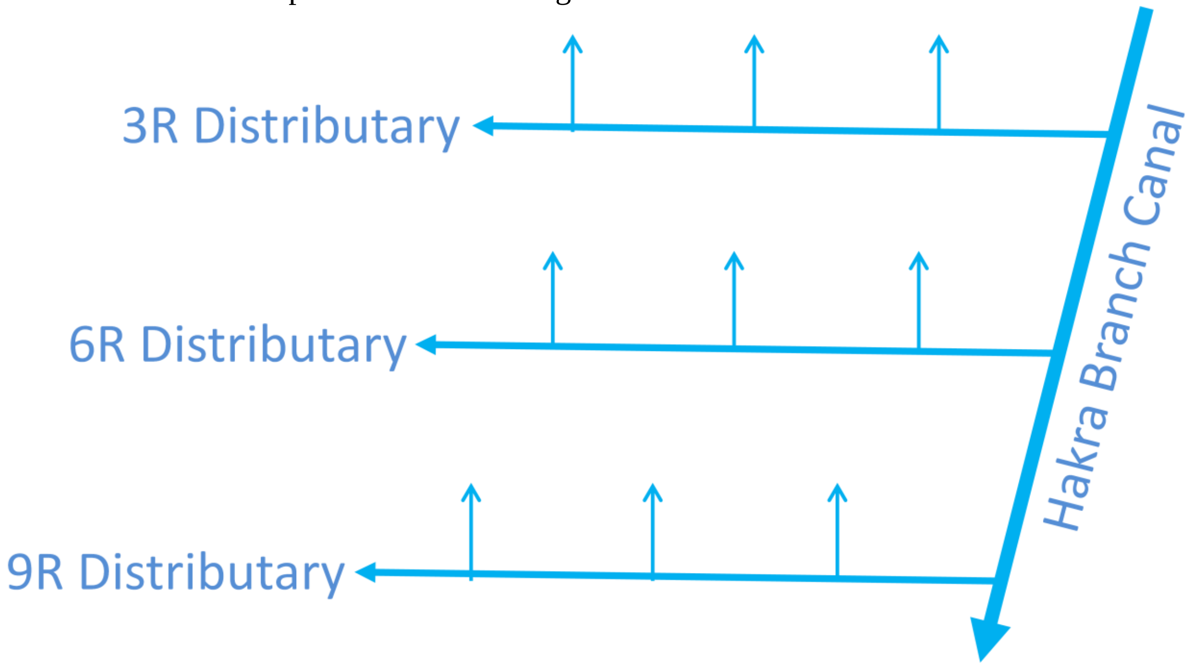


Figure 3b.

Overhead view of the Hakra Branch Canal – sampled secondary channels and outlet locations.

Figure 4a.
A typical Hakra Branch Canal distributory channel (secondary canal) with direction of low indicated.

Figure 4b.
A typical outlet structure on a Hakra Branch Canal distributory. Outlet draws water from the distributory channel.

Figure 5.
Water delivery heterogeneity and location on farmer profit.

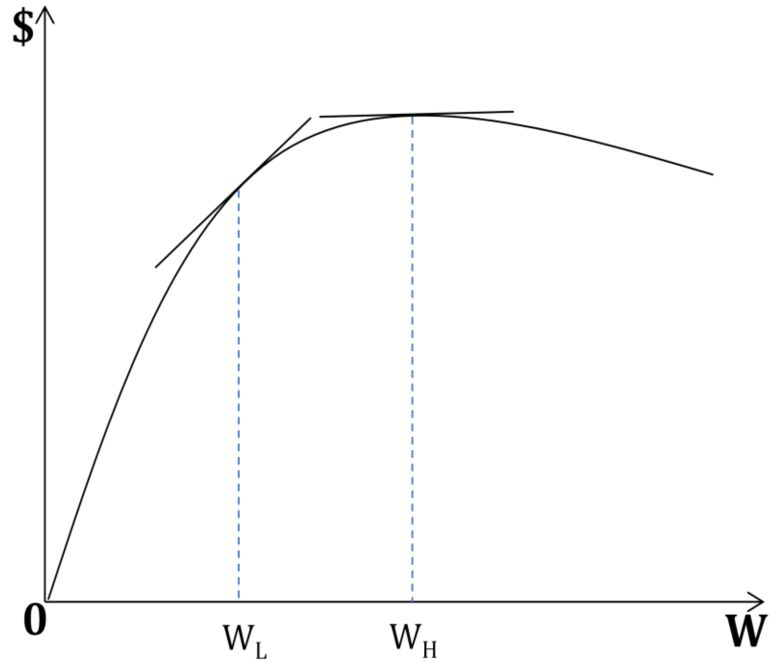
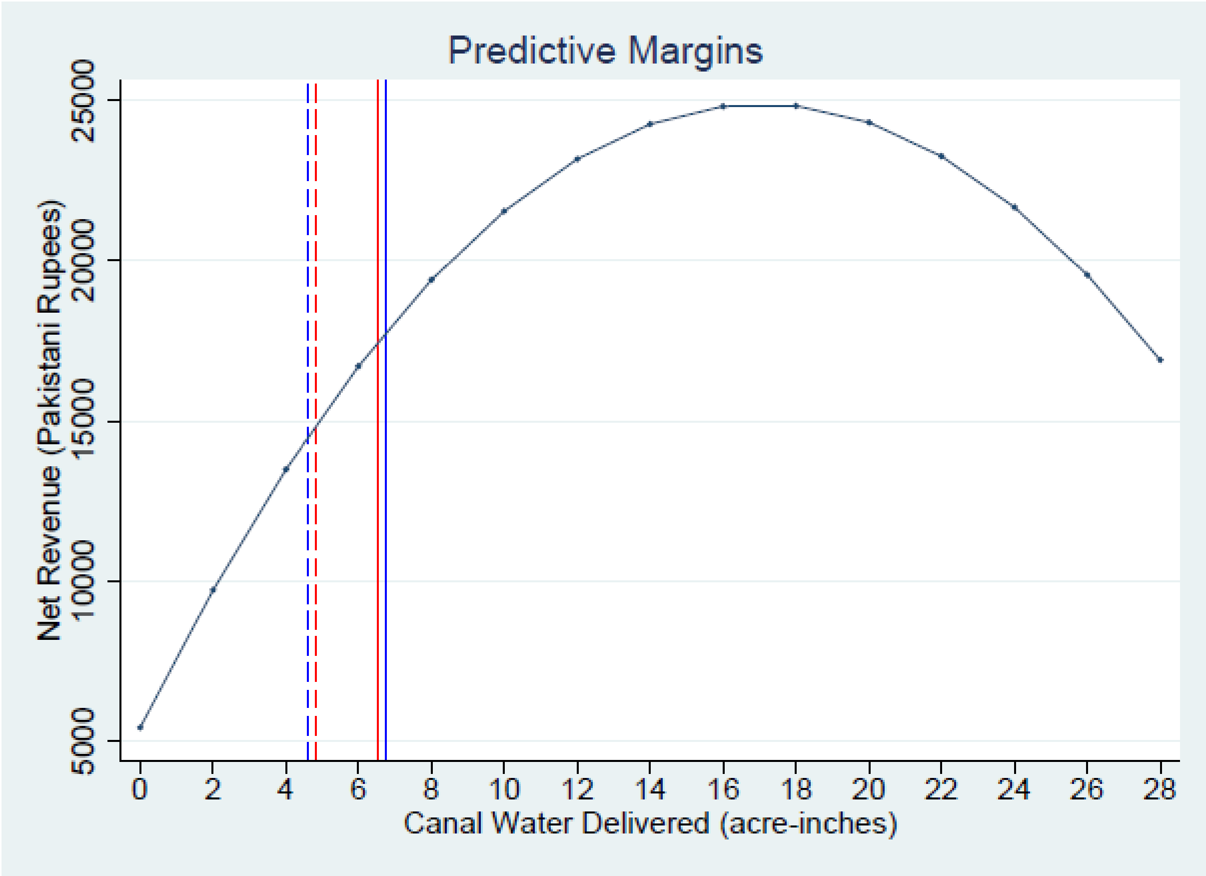
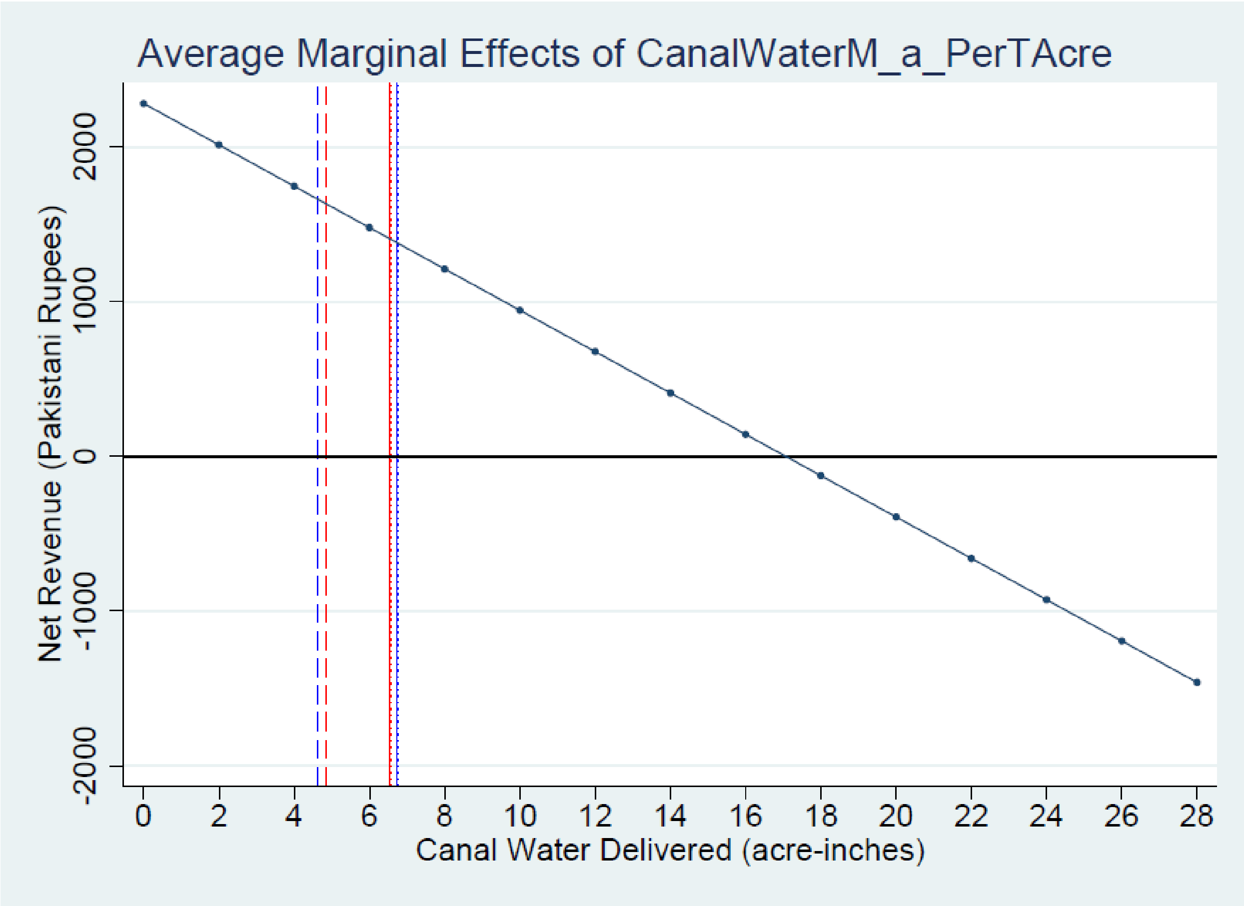


Figure 6a.
Estimated farmer profit as a function of water delivered (unadjusted for loss).



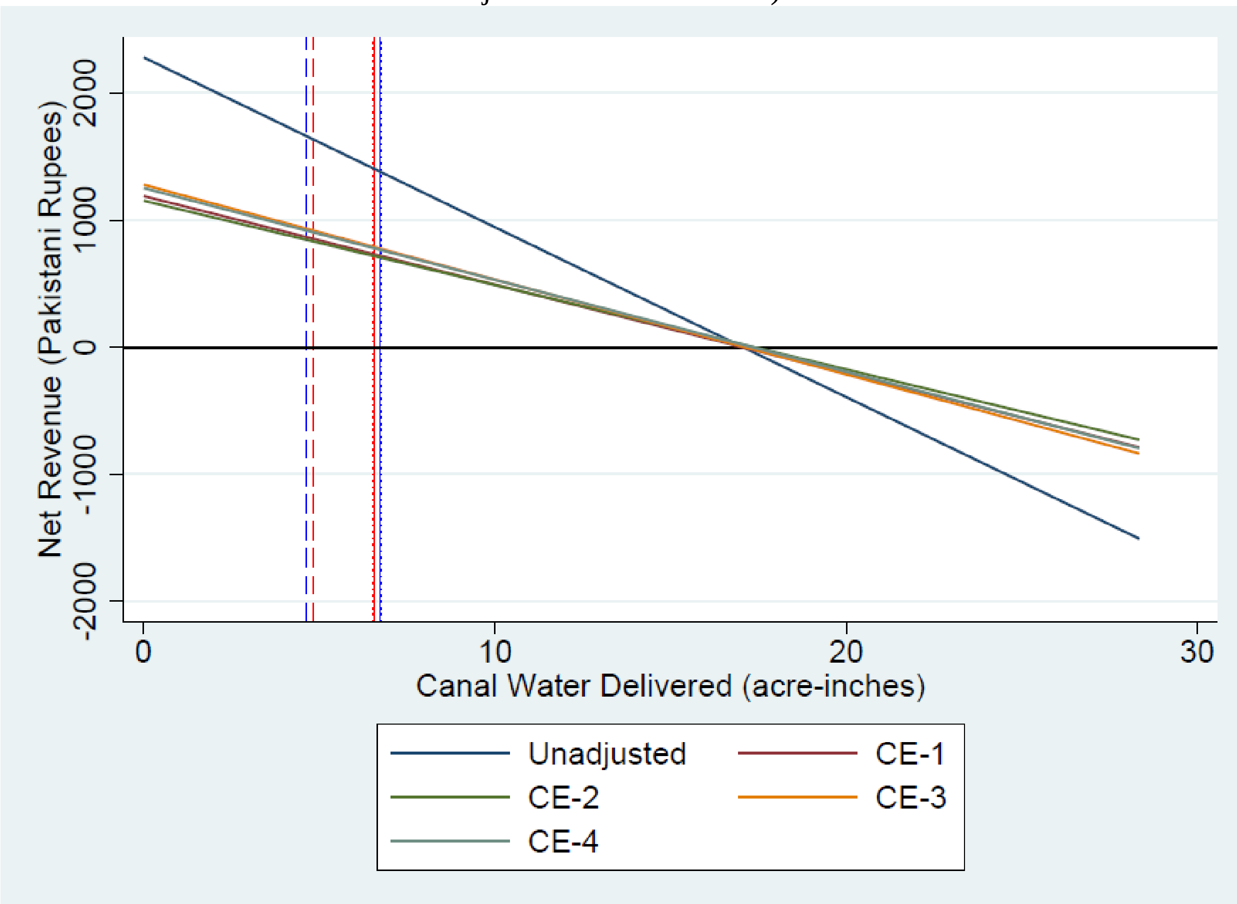
Dotted lines represent average water delivery to head segment farmers, solid lines represent average water delivery to middle segment farmers and dashed lines represent average water delivery to tail segment farmers. Blue lines refer to primary canal head, middle and tail while red lines refer to secondary canal head, middle and tail segments. Many times the head and middle segments receive equal quantities of water.

Figure 6b.
Estimated farmer marginal net revenues as a function of water delivered (unadjusted for loss).



Dotted lines represent average water delivery to head segment farmers, solid lines represent average water delivery to middle segment farmers and dashed lines represent average water delivery to tail segment farmers. Blue lines refer to primary canal head, middle and tail while red lines refer to secondary canal head, middle and tail segments. Many times the head and middle segments receive equal quantities of water.

Figure 7.
Estimated farmer marginal net revenues as a function of water delivered (with unadjusted and adjusted water deliveries).



Dotted lines represent average water delivery to head segment farmers, solid lines represent average water delivery to middle segment farmers and dashed lines represent average water delivery to tail segment farmers. Blue lines refer to primary canal head, middle and tail while red lines refer to secondary canal head, middle and tail segments. Many times the head and middle segments receive equal quantities of water.

Table 1. Relation between net revenues & canal water and distance

VARIABLES	(1) NR/ Acre	(2) CanalWater/ Acre	(3) TurnTime/ Acre	(4) Turns Received/ Acre	(5) Depth x Turns/ Acre
SecondaryDistance	-0.0499*	-2.12e-05**	0.00117	1.73e-06	-3.64e-06
	(0.0286)	(9.06e-06)	(0.0111)	(2.68e-06)	(4.86e-06)
TertiaryDistance	-23.99**	-0.00397	-9.253	-0.00193*	-0.00277
	(11.79)	(0.00323)	(5.749)	(0.00117)	(0.00208)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	2,463	6.797***	10,607***	0.938	1.746
	(8,344)	(2.195)	(3,239)	(0.765)	(1.407)
Observations	332	332	332	332	332
R-squared	0.132	0.154	0.216	0.165	0.158

Specification (1) has farmer net revenue per acre as the dependent variable. Specification (2) has measured canal water per acre (improved volumetric measure) as the dependent variable. In specification (3) the dependent variable is farmer reported number of turns received per acre In specification (4) the dependent variable is farmer reported season total irrigation time per acre. In specification (5) the dependent variable is farmer reported number of turns received multiplied by the perceived depth of field inundation per acre. The independent variables in all specifications include distance along the secondary canal segment, distance along the tertiary canal segment and controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 2. Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Number of members in household?	334	9.41018	5.771631	2	40
Number of Adults (18+ years)?	334	6.032934	3.703191	2	25
Number of household members that work?	334	2.47006	1.670447	0	15
How many years of formal education has the respondent had?	334	3.305389	2.138486	0	8
How many a year of formal education has the female head of HH had?	334	1.535928	2.141446	0	8
Have sons received any formal education?	334	0.961078	0.1937	0	1
Have daughters received any formal education?	334	0.946108	0.226144	0	1
How many years have you been managing farms?	334	18.28443	10.85171	1	60
How many years have you been involved in agriculture?	334	28.58982	12.54168	1	60
Have you had any contact with agricultural extension services?	334	0.434132	0.496386	0	1
Are you involved in livestock production?	334	0.928144	0.258637	0	1
Do you have formal sector loans?	334	0.206587	0.405464	0	1
Do you determine what to grow in the winter season based on summer season outcomes?	334	0.488024	0.500607	0	1
Positional preference: Main Hakra Canal?	334	1.149701	0.365621	1	3
Positional preference: Your Distributory?	334	1.266467	0.462674	1	3
Positional preference: Your Watercourse?	334	1.374251	0.615658	1	3
This land (plot 1) is inherited or bought (2 = inherited)?	334	1.982036	0.13302	1	2
If bought then purchasing amount (1)?	6	361666.7	474190.5	20000	1260000
This land (plot 2) is inherited or bought (2 = inherited)?	12	1.916667	0.288675	1	2
If bought then purchasing amount (2)?	1	140000	.	140000	140000
This land (plot 3) is inherited or bought (2 = inherited)?	7	2	0	2	2
If bought then purchasing amount (3)?	0				
This land (plot 4) is inherited or bought (2 = inherited)?	3	2	0	2	2
If bought then purchasing amount (4)?	0				
Planted Area (acres)	334	8.824551	10.41305	1	102
Land Value (Rs.)	334	6398428	7200800	0	91200000

Table 3a. Non-linearity and Traditional Water Measures (second-order polynomial)

VARIABLES	(1) NR/Acre	(2) NR/Acre	(3) NR/Acre
TurnsReceived/Acre	2,008		
	(1,773)		
(TurnsReceived/Acre) ^{2}	88.99		
	(106.9)		
TurnTime/Acre		-0.239	
		(0.314)	
(TurnTime/Acre) ^{2}		7.77e-06	
		(7.07e-06)	
(Depth x *Turns)/Acre*			342.2
			(615.1)
((Depth x *Turns)/Acre)* ^{2}			22.83
			(20.98)
Controls	*Yes*	*Yes*	*Yes*
Constant	3,562	6,170	1,724
	(7,645)	(8,547)	(7,560)
Observations	334	334	334
R-squared	0.190	0.117	0.176

In each specification the dependent variable is farmer net revenue and the independent variables are farmer reported measures canal water per acre delivered (and controls). In specification (1) the independent variable is farmer reported number of turns received per acre and its square. In specification (2) the independent variable is farmer reported season total irrigation time per acre and its square. In specification (3) the independent variable is farmer reported number of turns received multiplied by the perceived depth of field inundation per acre and its square. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 3b. Non-linearity and Traditional Water Measures (spline)

VARIABLES	(1) NR/Acre	(2) NR/Acre	(3) NR/Acre	(4) NR/Acre	(5) NR/Acre	(6) NR/Acre
TurnsReceived/Acre_Spl_a_i	10,539					
	(7,576)					
TurnsReceived/Acre_Spl_a_ii	-7,552					
	(7,652)					
TurnsReceived/Acre_Spl_b_i		2,367**				
		(1,191)				
TurnsReceived/Acre_Spl_b_ii		2,902				
		(2,580)				
TurnTime/Acre_Spl_a_i			-1.135**			
			(0.528)			
TurnTime/Acre_Spl_a_ii			1.436**			
			(0.628)			
TurnTime/Acre_Spl_b_i				0.0403		
				(0.228)		
TurnTime/Acre_Spl_b_ii				0.118		
				(0.658)		
Depth x *Turns/Acre_Spl_a_i*					4,313*	
					(2,426)	
Depth x *Turns /Acre_Spl_a_ii*					-3,411	
					(2,528)	
Depth x *Turns/Acre_Spl_b_i*						523.7
						(424.7)
Depth x *Turns /Acre_Spl_b_ii*						1,341
						(1,067)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	-1,557	3,417	13,026	3,588	-5,110	1,653
	(8,573)	(7,515)	(8,905)	(8,610)	(8,506)	(7,508)
Observations	334	334	334	334	334	334
R-squared	0.190	0.191	0.132	0.113	0.177	0.177

In each specification the dependent variable is farmer net revenue and the independent variables are farmer reported measures canal water per acre delivered (and controls). The independent variables are splines of the variables described in table 3a. Specifications should be seen as pairs i.e. (1) and (2), (3) and (4) and (5) and (6). Within each pair of specifications, the first specification splits the sample of farmers at the mean quantity of water delivered (denoted by the letter ‘a’ in the independent variable names), while the second specification splits the sample of farmers at the quantity of water that represents 50% of the maximum delivered (denoted by the letter ‘b’ in the independent variable names). Finally, the first spline segment is denoted by “i” and the second by “ii” in the independent variable names. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 4a. Non-linearity and Improved Water Measures

VARIABLES	(1) NR/Acre	(2) NR/Acre	(3) NR/Acre	(4) NR/Acre
CanalWater/Acre	1,984***	2,280***		
	(666.7)	(678.0)		
(CanalWater/Acre)^2	-52.81*	-66.81**		
	(31.64)	(31.95)		
CanalWater/Acre_Spl_a_i			2,536***	
			(690.3)	
CanalWater/Acre_Spl_a_ii			-1,855**	
			(793.2)	
CanalWater/Acre_Spl_b_i				1,425***
				(381.1)
CanalWater/Acre_Spl_b_ii				-2,190*
				(1,216)
Controls	*No*	*Yes*	*Yes*	*Yes*
Constant	5,161	-10,872	-10,224	-8,096
	(6,133)	(8,882)	(8,816)	(8,518)
Observations	334	334	334	334
R-squared	0.169	0.197	0.188	0.196

In each specification the dependent variable is farmer net revenue and the independent variables are canal water per acre delivered (and controls). In specifications (1) and (2) the independent variables are canal water per acre delivered and canal water delivered squared. Specification (3) splits the sample of farmers at the mean quantity of water delivered (denoted by the letter 'a' in the independent variable names), while specification (4) splits the sample of farmers at the quantity of water that represents 50% of the maximum delivered (denoted by the letter 'b' in the independent variable names). Finally, the first spline segment is denoted by "i" and the second by "ii" in the independent variable names in both specifications (3) and (4). Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 4a'. Specification (2) from Table 4(a) Shown with Control Variables

VARIABLES	(1) NR/Acre
CanalWater/Acre	2,280***
	(678.0)
(CanalWater/Acre)^2	-66.81**
	(31.95)
GroundwaterEC	8.797**
	(3.799)
GroundwaterEC^2	-0.00127**
	(0.000553)
Number of members in household?	-136.0
	(267.9)
Number of Adults (18+ years)?	-80.78
	(580.8)
Number of household members that work?	2,291***
	(735.4)
How many years of formal education has the respondent had?	-269.0
	(527.3)
How many a year of formal education has the female head of HH had?	393.3
	(646.0)
Have sons received any formal education?	-4,646
	(4,176)
Have daughters received any formal education?	2,471
	(3,592)
How many years have you been managing farms?	-195.7
	(136.1)
How many years have you been involved in agriculture?	-12.68
	(118.8)
Have you had any contact with agricultural extension services?	1,421
	(2,200)
Are you involved in livestock production?	6,353**
	(2,688)
Do you have formal sector loans?	2,110
	(3,254)
Do you determine what to grow in the winter season based on summer season outcomes?	-3,504
	(2,154)
Constant	-10,872
	(8,882)
Observations	334
R-squared	0.197

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4b. Marginal Net Revenue Functions Estimated with Adjustment to Water Measure

VARIABLES	(1) (MNR/Acre) *CE1	(2) (MNR/Acre) *CE2	(3) (MNR/Acre) *CE3	(4) (MNR/Acre) *CE4
CanalWater/Acre	-69.73***	-66.38***	-74.60***	-72.24***
	(0.767)	(0.986)	(0.786)	(1.007)
Constant	1,189***	1,153***	1,278***	1,253***
	(5.734)	(7.370)	(5.880)	(7.533)
Observations	332	332	332	332
R-squared	0.962	0.932	0.965	0.940

In each specification the dependent variable is farmer marginal net revenue and the independent variable canal water per acre delivered. Specification (1) uses canal water loss adjustment formula 1 (denoted by the CE1 in the dependent variable names), (2) uses formula 2 (denoted by the CE2 in the dependent variable names), (3) uses formula 3 (denoted by the CE3 in the dependent variable names) and (4) uses formula 4 (denoted by the CE4 in the dependent variable names). Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 5a. Water Delivered by Primary Canal Segment

VARIABLES	(1) CanalWater/ Acre	(2) CanalWater/ Acre_CE1	(3) CanalWater/ Acre_CE2	(4) CanalWater/ Acre_CE3	(5) CanalWater/ Acre_CE4
PrimaryHead	-0.867	-1.881	-2.757**	-2.006*	-2.524**
	(0.665)	(1.255)	(1.266)	(1.157)	(1.168)
PrimaryTail	-2.133***	-3.078***	-3.349***	-2.886***	-3.053***
	(0.589)	(1.117)	(1.127)	(1.030)	(1.039)
Constant	6.738***	12.52***	12.93***	11.64***	11.91***
	(0.404)	(0.763)	(0.769)	(0.703)	(0.710)
Observations	334	332	332	332	332
R-squared	0.038	0.023	0.029	0.024	0.029

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 5b. Water Delivered by Secondary Canal Segment

VARIABLES	(1) CanalWater/ Acre	(2) CanalWater/ Acre_CE1	(3) CanalWater/ Acre_CE2	(4) CanalWater/ Acre_CE3	(5) CanalWater/ Acre_CE4
SecondaryHead	-0.344	-0.140	-2.066	-0.692	-1.815
	(0.670)	(1.253)	(1.276)	(1.159)	(1.175)
SecondaryTail	-1.715***	-3.153**	-2.957**	-2.955***	-2.836**
	(0.657)	(1.232)	(1.254)	(1.140)	(1.156)
Constant	6.556***	12.24***	12.96***	11.53***	11.96***
	(0.510)	(0.953)	(0.970)	(0.881)	(0.894)
Observations	334	332	332	332	332
R-squared	0.025	0.028	0.017	0.024	0.018

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6a. Comparison of Marginal Net Revenue (MNR) by Primary Canal Location (values reported are marginal net revenues in Pakistani Rupees)

VARIABLES	(1) MNR_UnAdj	(2) MNR_CE1	(3) MNR_CE2	(4) MNR_CE3	(5) MNR_CE4
PrimaryHead	115.8	101.6*	124.1**	120.3**	135.5**
	(95.42)	(53.44)	(52.18)	(57.28)	(56.52)
PrimaryTail	285.1***	71.48*	66.54*	74.25*	70.93*
	(76.21)	(39.94)	(38.06)	(42.45)	(41.27)
Constant	1,380***	738.1***	717.7***	793.6***	779.1***
	(61.36)	(33.05)	(31.80)	(35.31)	(34.49)
Observations	334	332	332	332	332
R-squared	0.038	0.016	0.022	0.018	0.023

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6b. Comparison of Marginal Net Revenue (MNR) by Secondary Canal Location (values reported are marginal net revenues in Pakistani Rupees)

VARIABLES	(1) MNR_UnAdj	(2) MNR_CE1	(3) MNR_CE2	(4) MNR_CE3	(5) MNR_CE4
SecondaryHead	45.94	-19.65	94.74*	15.43	94.49*
	(95.12)	(52.38)	(51.09)	(56.11)	(55.26)
SecondaryTail	229.2**	84.87*	53.17	89.59	67.03
	(93.65)	(51.35)	(47.36)	(54.34)	(51.58)
Constant	1,404***	762.0***	716.7***	808.6***	777.1***
	(77.58)	(43.64)	(40.48)	(46.15)	(43.96)
Observations	334	332	332	332	332
R-squared	0.025	0.020	0.013	0.012	0.011

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 7. Difference in MNR – Adjusted vs. Unadjusted Water Measures

Hypothesis (paired t-test)	Result
MNR_Unadjusted – MNR_CE1	722.88***
	(17.14)
MNR_Unadjusted – MNR_CE2	739.71***
	(18.24)
MNR_Unadjusted – MNR_CE3	662.00***
	(15.92)
MNR_Unadjusted – MNR_CE 4	674.03***
	(16.78)
Observations	334

This table reports the results of a test of the difference in the average marginal net revenue across the two distributions generated by the unadjusted for canal losses estimation from specification (1) in table 4a (*MNR_Unadjusted*) and the loss adjusted specifications (1) – (4) in table 4b (*MNR_CE1*, *MNR_CE2*, *MNR_CE3* and *MNR_CE4*).

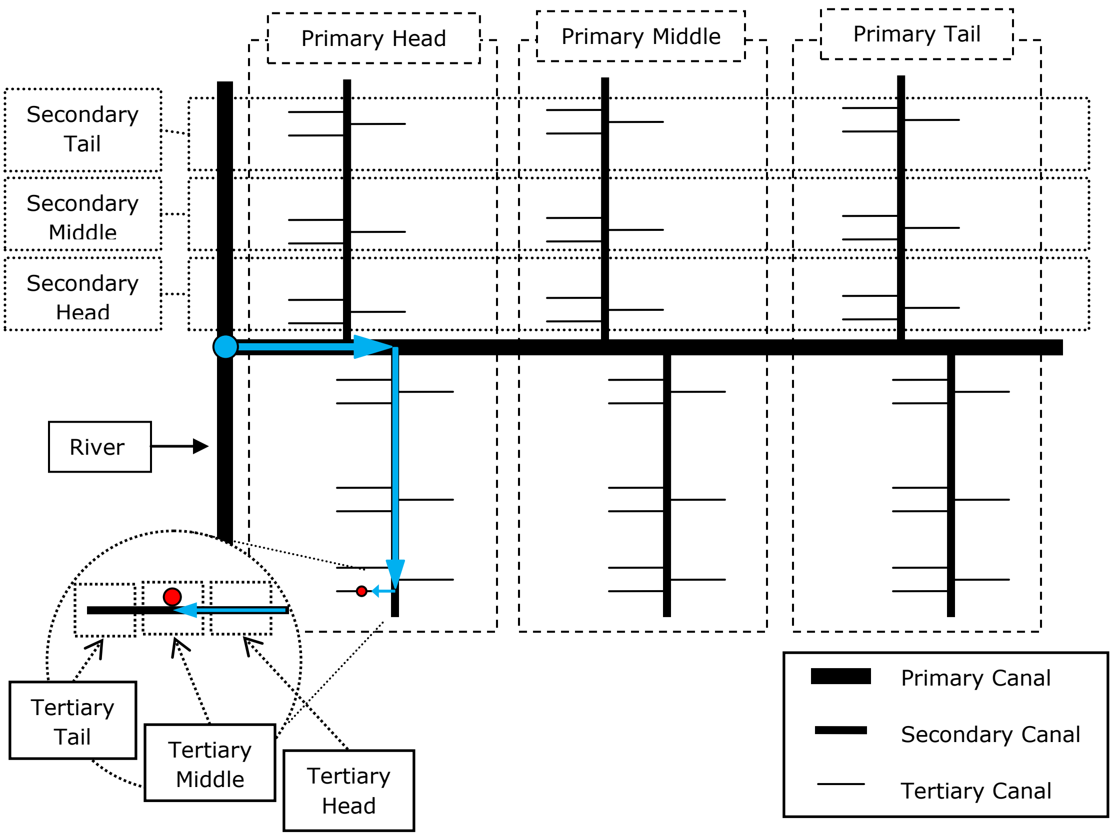
Table 8. Welfare Gains from Re-Allocation of Canal Water

Canal Water	*Efficient* *Allocation* Total Net Revenues (Rupees)	*Existing* *Allocation* Total Net Revenues (Rupees)	Gain (Rupees)	Gain (%)	Total Water Available (acre-inches)
Unadjusted	3,143,083	3,649,434	506,351	13.87%	2,437.477
CE-1	3,143,083	3,625,869	482,786	13.32%	3,643.949
CE-2	3,143,083	3,606,963	463,880	12.86%	3,679.264
CE-3	3,143,083	3,614,624	471,541	13.05%	3,366.882
CE-4	3,143,083	3,606,052	462,969	12.84%	3,393.224

This table reports the results of an optimization that re-allocated water to maximize system net revenues. The first row assumes that water can be reallocated without loss. Rows 2 to 5 use the 4 different calculations of conveyance efficiency when reallocating water.

Appendix: Conveyance Efficiency

One of the key hydrologic parameters of interest to this study is the delivery efficiency of water in the irrigation canal system, referred to as conveyance efficiency (CE). The figure below clarifies what exactly is being sought. Farmers are spread across the head, middle and tails of the primary, secondary and tertiary levels of the canal command. Let's say that one of the farmer's selected in our sample is indicated by the red dot. Water travels to a farmer (blue arrows) from the very head of the system (blue dot) to the farmer's field. Thus, CE is the water that actually reaches a farmer's field gate. What we want to estimate is the volume of water lost on the unit as it makes its way from the blue dot to the red dot.



Essentially, what is required is a basic hydrologic model of the canal system that includes CE as a model parameter. Secondary and tertiary canal segments in the Hakra Branch Canal have already been studied to determine CE using the inflow-outflow method to determine channel losses (Khan et al (1999)). Measuring loss using the inflow-outflow method requires careful measurement of flow at predetermined points in the canal and also requires calibration of all intermediate outflow structures (outlets on a distributory and farmgates on a watercourse). Primary canal segments have not been measured this way in any known study for Pakistan and specifically for the Hakra Canal System. However, discharge data for a long period of time is available and can be used to develop an estimate for CE.

Ideally, what we would like is that there is a channel segment specific CE term. That is, for each identifiable reach of the Hakra canal system, we can specify CE for each unit of distance travelled by water. At this stage (barring being able to go out and do an inflow-outflow study or another relevant field experiment), there is essentially one plan available to us. First, we will estimate the inter-distributory conveyance loss and intra-distributory conveyance loss using historic discharge data. For the tertiary canal segments no historic discharge data is available therefore we will rely on Khan et al's estimates of CE and transplant them for the segments of interest to us.

Primary Channel CE Estimates (Canal Head to Tail)

To estimate inter-distributory CE we need to develop a basic relation between CE and various channel segments using discharge data[‡]. The idea is fairly simple; let's start at the level of the Hakra Branch Canal (HBC) itself (the main stem from which the distributaries of interest i.e. 3R, 6R and 9R offtake).

The dataset used was all discharge data in the concerned distributaries from March 2006 up to November 2011[§]. In essence, we can rely on the simple idea of mass balance i.e. canal input should equal output unless there is loss. The idea relies on having complete data on input discharge and all offtaking discharge.

Thus at the primary level i.e. the main stem of the Hakra canal, we should find that,

$$\overline{q_{Loss}} = \frac{\sum_t^T (Q_t^{HB} - \sum_i^N Q_{ti})}{\sum_t^T (Q_t^{HB})}$$

‡ In all calculations, the average discharge was calculated for a given offtaking point for the summer period (May 1st to 30th October) for a period of 5 years (2006 to 2011).

§ The basic dataset provides canal name, date of record, discharge, capacity at head and culturable command area. The dataset is not ready to use as is and requires considerable cleaning, augmentation and completion.

Where $\overline{q_{Loss}}$ is average percentage loss, Q_t^{HB} is discharge at the Hakra Branch head at time t, Q_{ti} is discharge in distributory i at time t. This loss term applies to the entire length of the Hakra Branch and if we assume a linear relationship we can attribute a percentage loss to each foot of length. With this, we calculate loss of discharge up to the heads of the three distributaries of interest,

Distributory	**Percentage Loss in Discharge**
3R	0.089258
6R	0.163897
9R	0.252836

Secondary Channel CE Estimates (Distributory Head to Tail)

For secondary canals the simple method above does not apply since we do not have discharge at the head of off-taking outlets. What we do have instead is the discharge at the head of minor canals that offtake from distributaries which can be used to get a rough guide to conveyance efficiency in the secondary channels of interest.

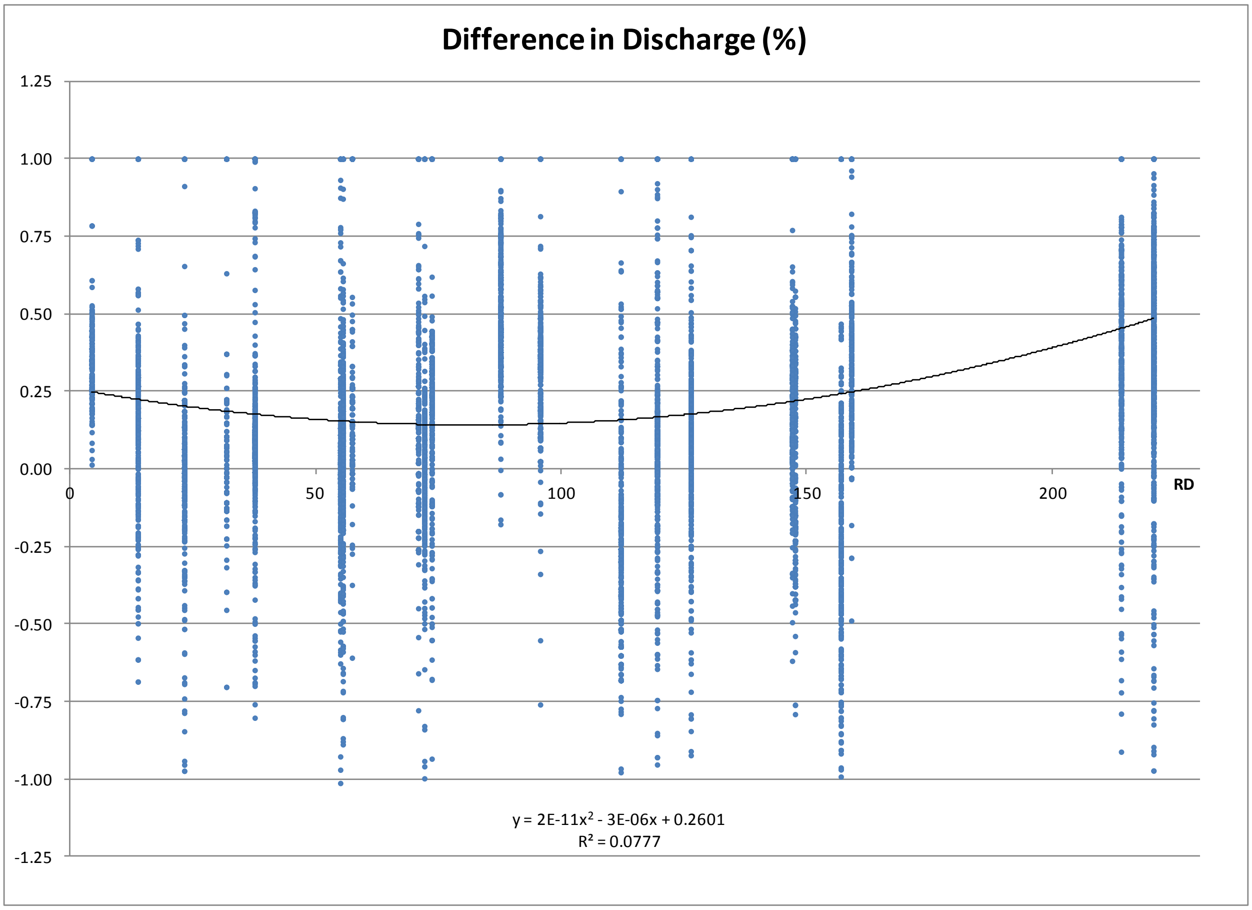
The distributaries in HBC have a total of 23 offtaking minor canals. This allows us to relate distributory distances to discharge at offtaking minor canals. We know the CCA, actual discharge and water allowance (the budgeted discharge) at each of these points (i.e., for both the distributaries and minor canals). To start with, we might consider the difference, D_{diff}, between the actual discharge per unit CCA at the head of a distributory, D_{head}, and the actual discharge per unit CCA at a given minor canal, D_i (we normalize by CCA so that the quantities being differenced are comparable),

$$D_{diff} = D_d - D_i$$

If this difference is positive, we can assume that there has been some loss between. As a first cut, the discharge per unit CCA should be roughly the same at both points. If there is a difference in discharge per unit CCA between the two points we can assume that the lost quantity can be attributed to conveyance losses. Using this method, the following was calculated,

$$d_{it}^{diff} = \frac{D_{dt} - D_{it}}{D_{dt}}$$

This gives a percentage loss per observation. Using this, we can relate distance from the head of a distributory to the head of a given minor canal observation; a second order polynomial relation is displayed in the graph below.



The second order polynomial relation between conveyance loss and distance is,

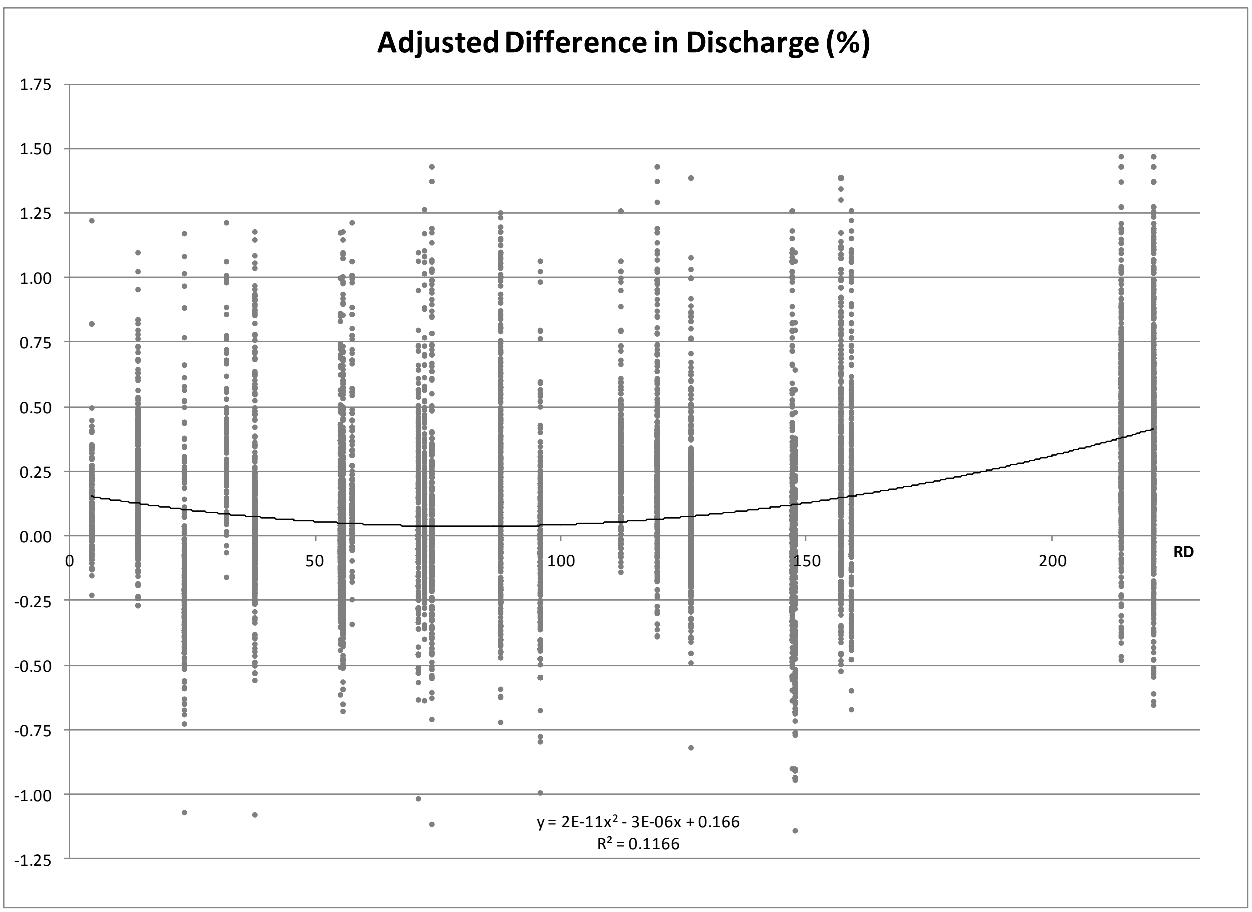
$$l = 0.00000000002d^2 - 0.000003d + 0.2601$$

Where l is percentage loss and d is distance in feet from the head of the channel segment.

An alternative method is as follows. It could be that the different minor canals may be assessed differently i.e. the water allowance may be different for different distributaries. A channel's command area is assessed by the irrigation department and is based on some presumed crop mix (once set these usually do not change). Thus, what we are really after is the difference between the ratio of actual discharge per unit CCA, D_{dt}, to assessed discharge per unit CCA, A_{dt}, at the head of the distributory and ratio of actual discharge per unit CCA, D_{it}, to assessed discharge per unit CCA, A_{it}, at a given minor canal head,

$$r_{it}^{diff} = \frac{D_{dt}}{A_{dt}} - \frac{D_{it}}{A_{it}}$$

Using this data the following relation emerges (again, using a second order polynomial).



The second order polynomial relation between conveyance loss and distance using adjusted discharge difference is,

$$l = 0.00000000002d^2 - 0.000003d + 0.1660$$

How do these estimates compare to some existing work?

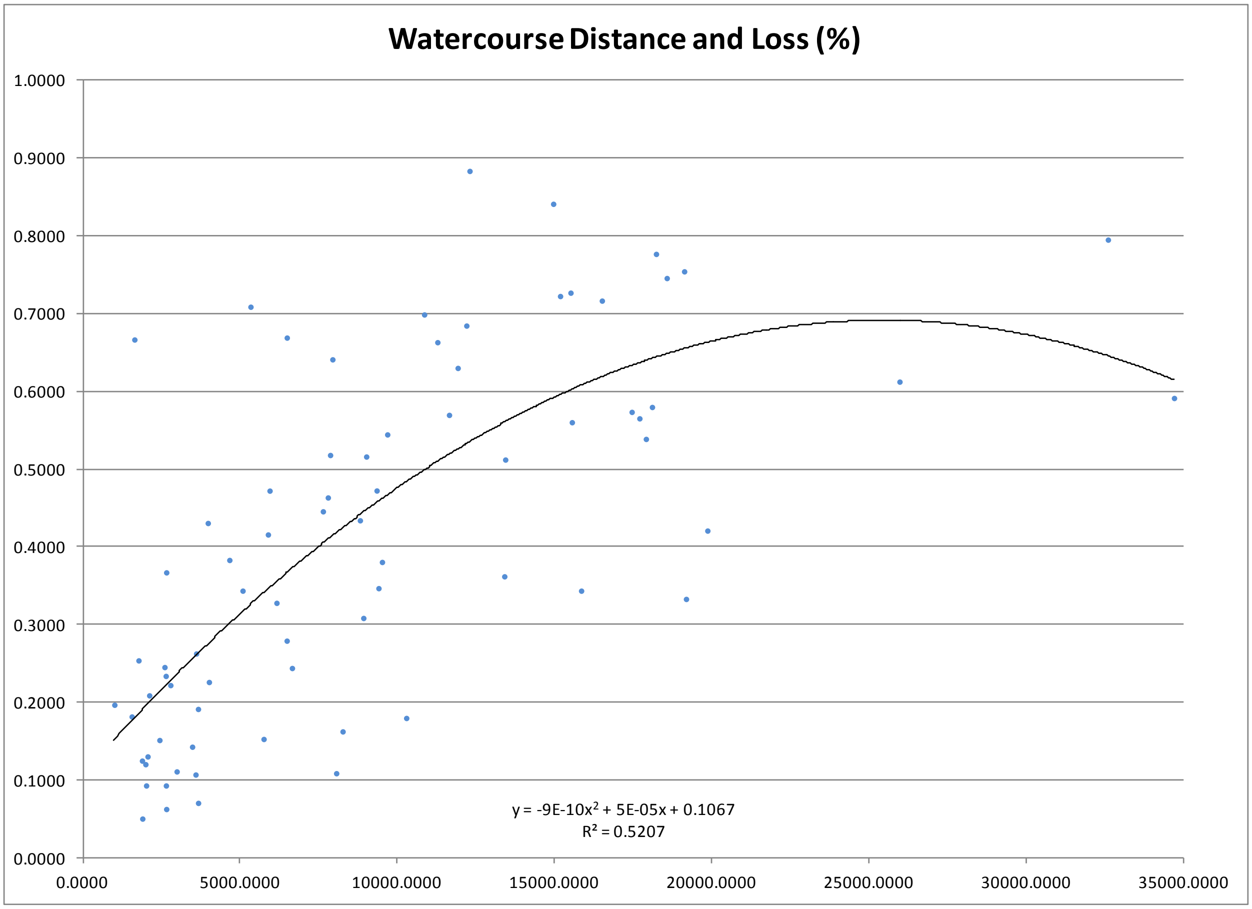
Study	**Distributory**	**Length**	**Reference Loss**	**Adjusted Difference in Discharge Estimate**	**Difference in Discharge Estimate**
Khan et al (1999)	3R	162300	0.15	0.21	0.30
Cheema et al (1999)	4R	112050	0.17	0.08	0.18

The estimates from the two models we have generated are not far off from these admittedly old estimates of conveyance loss. There really is no good way to judge how well our estimation does. Given the adjusted difference in discharge estimation makes an additional correction, we will choose it.

Tertiary Channel CE Estimates (Outlet Head to Tail)

For tertiary channels, we do not have any historic discharge data therefore we will have to rely on some existing estimate. Using Khan et al's study, we can derive a simple relation for watercourse CE. The study being referred to has average (over time) loss percentage for a set of watercourses across HBC. It provides loss percentage for the head, middle and tail of the watercourses selected[**]. We can use these to develop a simple relation between loss and distance (much like we did for primary and secondary canals). Using data from tables 20 and 21 from Khan et al's study, we develop the following relation.

[**] Basic data can be found in Khan et al's study and must be extracted and augmented.



The second order polynomial relation is,

$$l = -0.0000000009d^2 + 0.00005d + 0.1067$$

Where l is percentage loss and d is distance in feet from the head of the channel segment.

PART II

Farmer Adaptation to Heterogeneous Surface Irrigation Water Delivery[††]

Agha Ali Akram[‡‡]
Yale University

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Abstract

We use a unique dataset to analyse the impact of heterogeneous surface irrigation water supply on farmer choices in a large canal irrigation system in a developing country (Pakistan). Rather than rely on inaccurate and imprecise farmer perceptions, we collected carefully measured data on farmer water use through in-season physical volumetric measurements of surface water delivered. Additionally, agriculture production surveys on large canal systems often rely on farmer reports of location on the system (distance from origin), which can be accurate for a farmer's reported location on the local canal segment her plot is on but can be noisy for reported on location along the overall system. Thus, along with an improved water measure, we also collected precise measurements of farmer location on the canal system allowing for a better sense for distance from the origin.

Farmers adapt to reduced flows by reducing their overall planted area. Next, they modify their crop mix by switching from a water intense crop (cotton) to a crop that is less sensitive to water (millet). Finally, we consider input choice and find, not surprisingly, that most inputs are complementary to surface water irrigation and reductions in surface water deliveries result in reductions in use of other inputs. We explore two cases more thoroughly. First, we find that own-labour tends to increase as canal water decreases and we test to find that this tends to be a function of scale. Finally, we consider an input of special interest, groundwater, which we expected to act as a substitute to surface water. Instead, we see evidence of complementarity to surface water. This suggests that groundwater quality plays a distinct role in its usage and we do find evidence of groundwater quality modulating the amount of groundwater usage in tandem with surface water use.

JEL Codes: Q10, Q25

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[‡‡] School of Forestry and Environmental Studies, Yale University, New Haven.
E-mail: agha.akram@yale.edu.

1 Introduction

I use a unique dataset to analyse the impact of heterogeneous surface irrigation water supply on farmer choices in a large canal irrigation system in a developing country (Pakistan). Surveys of farmers on canal irrigation systems are able to capture the use of most inputs reasonably well (e.g. bags of fertilizer, litres of fuel etc). The one input that is usually not captured very well is canal irrigation water. To counter this, proxy measures for water availability are used such as number of irrigations applied, perceived depth of a typical irrigation and position along a canal system. However, these measurements tend to be rough; e.g. perceived depth applied is very dependent on a farmer's recall, his interpretation of depth as a measure and the assumption that water actually ponds in his fields so that a depth is in fact observable; measures of water availability based on position are often "lumpy" i.e. farmers are placed at the head or tail of the system rather than at a measured distance from its origin.

This paper uses actual physical measurements of both surface water delivered (in-season) and distance from the canal system's origin rather than relying on crude farmer perception based proxy measures for surface irrigation water availability. I measured canal water discharge using a flow meter in the Hakra Branch Canal system during the summer 2012 growing season. I also used a GPS device to spatially locate points along this system where measurements were made which also allowed me to better locate farmers. This was followed by a production survey of farmers once the summer growing season was over (a production survey is conducted post-season once all outcomes have been realized).

To motivate this paper, I regressed farmer net revenue (NR) on two measures of water availability: distance from the head of the canal system and a direct volumetric measure of surface water volume delivered. I find that as less (more) water becomes available to farmers NR per acre declines (increases) (see table 1 and figure 1). Thus heterogeneity in water availability has real impacts (reduced NR). What is it that farmers do in response to reduced surface water availability? We find that farmers adapt their behaviour in response to reduced canal water irrigation flows. Specifically, we test for the amount of land they plant and find that they reduce the amount of land planted. Next, we test for the possibility that farmers adapt their cropping mix. We find that farmers change their crop mix as a response to reduced flows, substituting to more water efficient crops. The two major crops grown by farmers in this system are cotton (thirsty) and millet (water efficient). I find evidence that farmers switch to producing more millet the further along the system they are (the less water is available to them). Finally, we look at water availability impacts on inputs including capital inputs (fertilizer, tractor), labor and groundwater use. We explore groundwater use more thoroughly and find that farmers not only modulate their groundwater use in response to surface water availability but also simultaneously as a function of the local groundwater quality engaging in optimal mixing of sub-standard groundwater with high quality surface water.

1.1. Context

The following is drawn from Akram (2013). The Indus Basin Irrigation System (IBIS) is a continuous-flow, fixed-rotation system with a significant network of infrastructure regulated by two major multi-purpose storage reservoirs: Mangla and Tarbela, a series of barrages, inter-river link canals, 45 major irrigation canal commands and over 120,000 watercourses delivering water to farms (Yu et al, 2013). Figure 2a shows a (grossly) simplified representation of the entire system with head waters located in the Himalayas and final exit into the Arabian Sea, with canal commands along the way.

Each of the 45 main canal commands (or canal systems) can be broken down into three distinct levels: (1) primary or main canals; (2) secondary canals or water channels (also referred to as distributaries and minors); and (3) tertiary canals or watercourses. The structures mediating discharge between canal commands and, within them, between primary and secondary canals are adjustable in nature, i.e. they tend to be gates that can control discharge. An outlet is the point at which water from a secondary canal is transferred to a tertiary canal.

The current management of the system has two tiers separated at the outlet structure (i.e. where the secondary and tertiary canals meet). The first tier is essentially controlled by government institutions and runs all the way down to the control of discharge between distributaries (secondary canals). However, as a result of recent reforms, Farmer Organizations (FOs) sometimes play a role water distribution at the distributory level. The second tier is farmer managed at the watercourse level (tertiary canals). See figure 2b to get a sense for the tiered nature of the irrigation system.

At the highest level, the Indus River System Authority (IRSA) manages and allocates water to the four provincial irrigation departments. The irrigation department in each province, known as the Provincial Irrigation and Drainage Authority(PIDA), prepares a Provincial Irrigation Demand (PID) on a 10-day basis for IRSA, which is responsible for making releases from the three major reservoirs based on projected demands(Tarbela, Mangla and Chashma) (National Water Policy, 2004). Once IRSA allocates water, the PIDA assumes responsibility for distributing that water internally within the canal commands under its jurisdiction. PIDA supplies canal water to farmers, and it manages, operates and maintains the entire irrigation network, except the tertiary canals that farmers maintain (Latif, 2007). Although the Provincial Irrigation Department prices water, this price bears no relation to the actual market price of water (or the actual quantity of water delivered).

At the tertiary (watercourse) level, the system of water allocation in Pakistan is called *warabandi*, literally translated as “turns” (wahr) which are fixed (bandi). The warabandi system consists of a continuous rotation of water in a cycle lasting 7-10.5 days; each farmer in the watercourse will receive water once for a fixed time during each cycle (Bandaragoda, 1998). This cycle starts at the head of a watercourse and progresses to the tail, and during an allotted time-segment within a cycle a farmer has the right to use all of the water flowing in the watercourse.

1.2. Literature Review

Much has been written about water in agriculture and water in Pakistan’s agriculture specifically. A large literature exists that could broadly be classified as taking an irrigation engineering perspective. This includes for instance Latif (2007), Latif and Sarwar (1994), Skogerboe et al (1998), Munir, Kalwij and Brouwer (1999) and Bhutta & van der Velde (1992). These studies typically look at the physical system and/or associated institutional management to either estimate the impact of a given system parameter or the impact of an improvement in that parameter. As an example, Latif and Sarwar (1994) estimate the improvement in water delivery to tertiary canals with changes to the existing irrigation water rotation. Skogerboe et al (1998) estimate channel losses in a selected set of canal reaches. These studies do not capture the economic implications of the surface water environment, thus are not able to inform policy in a complete manner.

Next there is an established literature that estimates agricultural production functions (for the Pakistani case, see Battese, Malik and Gill (1996), Sahibzada (2002)). Sahibzada (2002) estimates a production function and derives the demand function for irrigation water based on sample of farmers across Pakistan. Sahibzada aims to evaluate the impact on demand of different pricing schemes (efficiency price, average cost based) for irrigation water. She finds, "that irrigation water shortages are the result of the inflexibility of the present irrigation water supply system for agricultural use and have little to do with the existing water pricing practice in the country". Furthermore, she finds that demand is not particularly sensitive to price (price elasticity of demand is low). Like most studies that focus on the estimation of production functions, the goal is to estimate changes in factor demand with exogenous price changes. Critically, Sahibzada's estimation (and for that matter, any production function estimation exercise) relies on farmer reported water use.

Next, there is a large literature on water allocation efficiency (this is not specific to Pakistan) both theoretical (Tsur and Dinar (1997), Tsur (2009) and Chakravorty and Roumasset (1991)) and applied (Berck et al (1990), Hurd et al (1999), Xun et al (2005, 2013), Jeuland (2010), Yang et al (2014)). Water allocation in a basin is one of the classic problems of allocation and efficiency. In this regard, Hurd et al (1999) provide a good sense for what goes into water allocation models. They use what they term a spatial equilibrium model that joins regional water supply functions and demand functions for specified uses with a linear representation of the water delivery system. The basis for Hurd et al's theory is the work of Hartman and Seastone (1970). The basic rule that emerges is that the marginal value of water adjusted for return flows is equated across users. The, an efficient allocation is devised based on this rule. The trouble with a lot of studies that use large, basin-scale hydro-economic optimizations is that the underlying water demand functions are poorly understood and even more poorly modeled.

The model that is currently used for studying water allocation in Pakistan's agriculture is the Indus Basin Model – Revised (IBMR). The IBMR optimizes water allocation amongst agricultural water users in Pakistan to maximize net social product i.e. the sum of net producer and consumer surplus. Agricultural production and consumption is simulated within nine agro-climatic zones (ACZ). These ACZs are connected via canals and river segments. Within each zone there are production possibilities for up to fifteen crops. Water availability and usage are very detailed in the model. Each crop requires water in different quantities and at different times (on a monthly basis). The actual water requirements are reduced by the expected effective rainfall and that available from subirrigation (transpiration from groundwater as a result of capillary action). Both sources differ by zone, and subirrigation differs by the fresh/saline distinction within each zone because the depths to water table differ. Mixing of subsurface irrigation supplies with surface water is restricted to acceptable ratios in saline areas. The remaining crop requirements must be met from surface water, supplemented in fresh areas by private tubewell operations up to the limit of the installed capacity plus any endogenously-determined private investment in new tubewells. Where applicable, government tubewell operations are simulated to augment the surface supplies. Within a zone, the surface flows from the canal heads are reduced for canal losses and again for watercourse and field losses prior to reaching the crops. The linear programming format of the IBMR uses the maximization of the sum of consumers' and producers' surpluses. Use of this objective function ensures that farmers will choose cropping patterns and input usage which maximizes their incomes while at the same time equating consumer demands with product supplies via adjustment in market prices. Thus a solution to the IBMR gives not only a simulated water distribution pattern, production by crop, technology, and zone, and the input use required for that production, but market-clearing prices and hence farm income as well.

Finally, some work suggests that farmers using the existing relatively rigid irrigation system are dynamic and adaptive, and have introduced a small degree of flexibility in the system. In a study of the Fordwah/Eastern-Sadiqia Canal area, Strosser and Kuper (1994) found an active water market. They reported that the vast majority of farmers in their study area were involved in the buying and selling of water (see also Meinzen-Dick & Sullins (1994)). The bulk of water sales and purchases were groundwater. Groundwater sales are constrained spatially to farmers who are close by and on the canal network, since selling water to farmers, who are very far away or not part of the canal system, makes the transactions costs unattractive (as an example, information frictions will enter as distance between buyers and sellers increases; since buyers and sellers must be able to locate each other and the further away they are spatially the harder it will be to locate each other; another example of increasing transaction cost as distance between buyer and seller increases is conveyance efficiency). Groundwater is, however, relatively easier to sell, since it is not bound by a schedule, like surface irrigation water.

Given the above review, not much seems to have been written on the nature of adaptations that farmers make. It has generally been noted that farmers further down the canal system are delivered less water from it. Given this heterogeneity in water delivery, they must adapt their agricultural production practices. This study attempts to discover some of these adaptations.

There is a literature that examines farmer outcomes in relation to water availability. One strand tends to be somewhat limited (and not allied with economic science). The International Water Management Institute (IWMI) has produced reports on yield (output per unit land) in selected canal works in India and Pakistan. For instance, Hussain et al (2003) analyse wheat productivity along select canals in Pakistan and India. They find that yields per hectare are significantly lower further down the length of the canals they study. Irrigation engineering literature also weighs in on this issue in a similar vein. For instance, Latif (2007) finds, like Hussain et al (2003), that farmers at the tail reaches of canal systems tend to have lower yields.

More firmly in the economics literature, is a suite of studies that look at farmer adaptation to climate change (e.g. Kurukulasuriya and Mendelsohn (2008), Seo and Mendelsohn (2008)). These studies typically estimate the impact of existing variation in temperature and precipitation on farmer crop choice, farm type and the choice to use irrigation. Temperature and precipitation are both exogenously varying agricultural inputs therefore provide a basis to study the kinds of choices that farmers make in response to different climatic conditions. The key idea of utilising an exogenous farming input in farmer choice will be something I do in my study.

Farmer production choice in response to agricultural water availability is something that seems to be somewhat scarce in the economics literature. Certainly, the impact of water availability on farmer revenues and yields has been studied. Meinzen-Dick (1996) analyses the impact of surface and groundwater on Pakistani farmer yields and revenues, while Meinzen-Dick (2002) analyses the impact of farmer participation in local associations as a response to water availability along canals in India (though again, it must be emphasised that the measures of water used are not direct volumetric measurements of farmer water consumption).

In some sense, Hornbeck and Keskin (2013) come closest in spirit to my study in that they analyse most directly farmer crop choices with regard to water access. Specifically, they look at the impact that access to Ogallala Aquifer water has on farmer choices of crops sown under a drought overhang. They compare similar counties nearby, over time, to counties that access the Ogallala. They find that after initial access to the Ogallala, land values increased in Ogallala counties. Specifically, they find that not only do farmers irrigate their land more but that the total quantity of land under cultivation increases as well. However, farmers began shifting to more water intense crops after gaining access to Ogallala water and this, in turn, meant that they were more sensitive to drought. My study links canal irrigation water availability to farmer land and water allocation choices.

2 Theory

This section follows Hornbeck and Keskin (2013). Our basic set up is as follows,

$$\max_{L_1,L_2,w_1,w_2} \{y_1(L_1, w_1) + y_2(L_2, w_2)\} \tag{1}$$

Subject to,

$$\begin{aligned} L_1 + L_2 &= \bar{L} \\ w_1 + w_2 &= \bar{w} \end{aligned} \tag{2}$$

Where, y_i is a globally concave net benefits function, L_i is the area of land allocated to crop i and w_i is the volume of water allocated to crop i, while $\bar{L}$ and $\bar{w}$ represent the area of land and water available to the farmer. Crop 1 is assumed to be a water intense crop (in our case, let us say cotton) and crop 2 is assumed to be a water efficient crop (in our case let us say millet). As in Hornbeck and Keskin's analysis, we assume that:

- Marginal product of water is higher for the first crop i.e. $\frac{\partial y_1}{\partial w_1} > \frac{\partial y_2}{\partial w_2} > 0$

- Marginal product of water declines slower for the first crop i.e. $\frac{\partial^2 y_2}{(\partial w_2)^2} < \frac{\partial^2 y_1}{(\partial w_1)^2} < 0$.

- Water and land are complementary for both crops and weakly more so for the first crop i.e. $\frac{\partial^2 y_1}{\partial L_1 \partial w_1} \geq \frac{\partial^2 y_2}{\partial L_2 \partial w_2} > 0$

First order conditions assuming an internal solution are,

$$\frac{\partial y_1(L_1^*, w_1^*)}{\partial w_1} - \frac{\partial y_2(\bar{L} - L_1^*, \bar{w} - w_1^*)}{\partial w_2} = 0 \tag{3}$$

$$\frac{\partial y_1(L_1^*, w_1^*)}{\partial L_1} - \frac{\partial y_2(\bar{L} - L_1^*, \bar{w} - w_1^*)}{\partial L_2} = 0 \tag{4}$$

For an exogenous increase in $\bar{w}$ we totally differentiate the first order conditions and see that,

$$\begin{aligned}\frac{\partial^2 y_1(L_1^*, w_1^*)}{\partial w_1 \partial L_1}\frac{\partial L_1^*}{\partial \bar{w}} + \frac{\partial^2 y_1(L_1^*, w_1^*)}{(\partial w_1)^2}\frac{\partial w_1^*}{\partial \bar{w}} - \frac{\partial^2 y_2(\bar{L} - L_1^*, \bar{w} - w_1^*)}{(\partial w_2)^2}\left(1 - \frac{\partial w_1^*}{\partial \bar{w}}\right) \\ + \frac{\partial^2 y_2(\bar{L} - L_1^*, \bar{w} - w_1^*)}{\partial w_2 \partial L_2}\frac{\partial L_1^*}{\partial \bar{w}} = 0\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{\partial^2 y_1(L_1^*, w_1^*)}{\partial w_1 \partial L_1}\frac{\partial w_1^*}{\partial \bar{w}} + \frac{\partial^2 y_1(L_1^*, w_1^*)}{(\partial L_1)^2}\frac{\partial L_1^*}{\partial \bar{w}} - \frac{\partial^2 y_2(\bar{L} - L_1^*, \bar{w} - w_1^*)}{(\partial L_2)^2}\frac{\partial L_1^*}{\partial \bar{w}} \\ + \frac{\partial^2 y_2(\bar{L} - L_1^*, \bar{w} - w_1^*)}{\partial w_2 \partial L_2}\left(1 - \frac{\partial w_1^*}{\partial \bar{w}}\right) = 0\end{aligned} \tag{6}$$

The solution to this system is,

$$\frac{\partial L_1^*}{\partial \bar{w}} = \frac{\left(\frac{\partial^2 y_1}{(\partial w_1)^2} + \frac{\partial^2 y_2}{(\partial w_2)^2}\right)\frac{\partial^2 y_2}{\partial w_2 \partial L_2} - \left(\frac{\partial^2 y_1}{\partial w_1 \partial L_1} + \frac{\partial^2 y_2}{\partial w_2 \partial L_2}\right)\frac{\partial^2 y_2}{(\partial w_2)^2}}{\left(\frac{\partial^2 y_1}{(\partial w_1)^2} + \frac{\partial^2 y_2}{(\partial w_2)^2}\right)\left(\frac{\partial^2 y_1}{(\partial L_1)^2} + \frac{\partial^2 y_2}{(\partial L_2)^2}\right) - \left(\frac{\partial^2 y_1}{\partial w_1 \partial L_1} + \frac{\partial^2 y_2}{\partial w_2 \partial L_2}\right)^2} \tag{7}$$

$$\frac{\partial w_1^*}{\partial \bar{w}} = \frac{\left(\frac{\partial^2 y_1}{(\partial L_1)^2} + \frac{\partial^2 y_2}{(\partial L_2)^2}\right)\frac{\partial^2 y_2}{\partial w_2 \partial L_2} - \left(\frac{\partial^2 y_1}{\partial w_1 \partial L_1} + \frac{\partial^2 y_2}{\partial w_2 \partial L_2}\right)\frac{\partial^2 y_2}{\partial w_2 \partial L_2}}{\left(\frac{\partial^2 y_1}{(\partial w_1)^2} + \frac{\partial^2 y_2}{(\partial w_2)^2}\right)\left(\frac{\partial^2 y_1}{(\partial L_1)^2} + \frac{\partial^2 y_2}{(\partial L_2)^2}\right) - \left(\frac{\partial^2 y_1}{\partial w_1 \partial L_1} + \frac{\partial^2 y_2}{\partial w_2 \partial L_2}\right)^2} \tag{8}$$

Then, since the denominators are positive due to concavity of the benefits function and the assumptions made, we see that $\frac{\partial L_1^*}{\partial \bar{w}} > 0$ and $\frac{\partial w_1^*}{\partial \bar{w}} > 0$. What this tells us is that as the endowment of water increases, both land and water allocated to the water intense crop increases.

3 Data

3.1. Data Collection: In-season Water Measurement and Distance Recordings

The data set I use for this study is unique. In particular, two features set it apart from most other agriculture and irrigation datasets. The first feature is collection of in-season water discharge data. Many agricultural surveys tend to gather either crude measures of irrigation such as the amount of land irrigated or then collect farmer perception data such as perceived depth of irrigation applied (which, incidentally, is likely endogenous since depth perceived may be affected by the amount of land a farmer plants). I selected three distributaries along the Hakra Branch Canal – namely 3R, 6R and 9R (the 'R' stand for right-bank of the canal) – from which I then proceeded to select and measure discharge in watercourse outlets. I measured discharge in as many watercourses as I could along the distributory. This was somewhat opportunistic but I was able to measure discharge in at least two-thirds (if not more) of all watercourses on the primary distributory trunk for all three distributaries. The measurement of discharge followed standard stream measurement protocol where the stream was divided into cross-sectional segments and flow was recorded in each segment separately[§§]. Flow was measured using a "Flowatch Flowmeter/Anemometer" (as the name implies, it had a wind speed gauge too). The total process took 12 days from start to end and included one measurement of discharge per outlet selected. As might be apparent, this is a snapshot and not a season level measurement. If we assume that discharge across the outlets measured is proportional, then this snapshot provides a good guide for relative discharge levels. The season level water volume calculation may not be very accurate but certainly we will know where outlets stand in comparison to each other in terms of discharge.

The second unique feature of this data set is a relatively precise measure of distance along the canal system. Distance along a canal is also seen as a good proxy measure of water

[§§] Please contact author for the procedure used.

availability (see: Meinzen-Dick et al (2002)). However, it is often crudely measured, where farmers are lumped into the head, middle or tail of a canal segment. If a survey is able to collect distance, it typically relies on a farmer's report of the distance. This may not be entirely reliable as farmers may not be keenly aware of all distance measures that lead up to their plot. In the case of this study, there are three distinct distance components (as shown in figure 2b) – a primary distance, a secondary distance and tertiary distance. Primary distances can be had from public records but secondary and tertiary distances must either be measured or sought from farmers. Public records of secondary distances, i.e. distance from the head of the secondary canal up to an outlet structure on which a farmer's plot may be found do exist, but the naming scheme is different to that on the ground. Thus, based on my own field experience, a farmer may know that he is on outlet structure 57-B but the public record will only speak to an outlet on a given bank of the distributory with a given distance from head (the public record does not associated the distance measure with the outlet structure number). Thus, one must rely on the farmer's report of the distance from the head of the system, which may or may not be correct (farmers are keenly aware of their tertiary distance i.e. distance from the head of the watercourse but their knowledge of the exact distance from the head of the distributory can be patchy). I used a GPS device to locate each point that I made water measurements at. This meant I could plot these points in a GIS file and carefully (to within a few feet) place an outlet structure along the canal (outlet structures are the points where I made water discharge measurements). I used ArcGIS which has a basic satellite image available of the Earth as a background. Using a combination of my GPS points and the available ArcGIS satellite image, I was not only able to trace out the irrigation system I was studying but also locate outlets on it. Thus, I could calculate (using ArcGIS) the distance from the head of the canal system to any given outlet structure along a distributory. This also meant that I could direct the survey team that did the post-harvest survey to survey farmers at specific locations.

3.2. Data Collection: Post-season Production Survey

A full production survey was conducted after the summer 2012 growing season (locally called *Kharif*). We collected production data from farmers along select distributaries (3R, 6R and 9R). Data was collected on output by plot crop and input by plot crop. Special interest was paid to the collection of surface irrigation water use and groundwater use. For surface water use, we asked farmers about the number of turns they got, the turn time and also their perceived depth of water applied. Calculating groundwater use requires the collection of data on pump age, power and depth of the bore. Along with this, we also asked farmers basic socio-economic questions to act as possible controls.

This, two step (asynchronous) data collection posed a challenge. Typically, production data for a season is collected once the season is over, since all outcomes have been realized. But I measured discharge in-season, which meant that I had to then locate farmers post-season on the watercourses I measured discharge on. This meant that I had to work closely with local irrigation officials to make sure I was able to record the correct name of a given watercourse (this is important – public records state only distances not watercourse names). Watercourse names are critical as they allow one to associate a watercourse with a village. The issue that then emerges is a logistical one. I travelled along the length of a canal to make my measurements: (1) the road next to a canal is very difficult to travel along (requires a compact 4x4 vehicle) and (2) farmers (who I intended to survey) reside in villages, not at the head of a watercourse. Thus, watercourses then had to be associated to villages – which is why I made sure I collected watercourse names at the time of discharge measurement. Once the universe of villages was discovered, I could dispatch my survey team to randomly sample within a village (the criteria to be a valid survey respondent was to be a farmer on the watercourse in my list).

3.3. Variable of Special Interest: Surface Water Volume

As stated, one of the key variables of interest (and one that differentiates this dataset) is surface water volume used by farmers over the course of the growing season. I collected three crucial pieces of information that help construct this measure: the amount of time a farmer kept his farm gate open at each turn (time per turn), how many turns he received in the growing season (turns) and finally watercourse discharge (volume per unit time). Then, to get season level water volume delivery to a given farmer, I multiply these three components. Note that all three components are objective in that farmers turn times are set externally as are the number of turns received. Discharge of course is an objectively measured number. Thus, our measurement of this important exogenous phenomenon is does not rely on farmer perception in any way.

3.4. Summary Statistics

Table 2 provides some summary statistics. Our complete sample contains 363 farmers. The average farmer in our sample has had 28 years of experience in agriculture, owns the primary plot of land he cultivates which is worth about Rs. 6.2 million.

4 Results

In the following analysis, we use two broad sets of specifications for which farmer adaptation: (1) volumetrically measured canal water delivered to farmers; and (2) three measures of distance from the origin of canal system – primary distance, secondary distance and tertiary distance – which serve as proxy measures of water availability. The latter set is one of the "traditional" ways of measuring water availability and serves as a consistency check for results from the first set of specifications.

4.1. Reducing Cultivated Land

First, we test whether farmers reduce their cultivated acreage as a response to reduced canal flows. To do this we use an array of specifications.

The first set of specifications we run uses the improved volumetric measure of water,

$$l_i = \alpha + \beta_1 W_i + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{9}$$

Where l_i is a measure of cultivated land, W_i is a direct in-season measure of surface water irrigation and $\boldsymbol{X_i}$ is a vector of controls. W_i is constructed as follows,

$$W_i = \frac{d_j . T_i}{A_i} \tag{9a}$$

Where d_j is the discharge measurement at the outlet structure of the watercourse, j, that farmer i is located on, T_i is the total season time that a farmer reported for irrigation to his farmland and A_i is the total land available. The results are presented in table 3a. Specification (1) uses the total amount of land cultivated by the farmer as the response variable while specification (2) uses the ratio of planted area to total available area (the total area available to potentially cultivate) for a farmer during the growing season. In both specifications we find strong evidence that a farmer tends to increase the amount of land he cultivates as the amount of canal water available increases.

Next, we use traditional measure of water availability, namely distance,

$$l_i = \alpha + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_3 D_i^3 + \boldsymbol{X_i \gamma} + \varepsilon_i \quad (10)$$

Where all is as before except D_i^j which is a measure of distance along the canal system from the point of origin (the typical proxy measure of water availability) and $j \in \{primary, secondary, tertiaty\}$. The results are presented in table 3(b). As before, we use two specifications and across specifications, it becomes quite clear that the amount of land being planted by farmers declines with a reduction in surface irrigation water availability (with greater distance along the system).

4.2. Crop Switching

Second, we test for farmers' crop switching. That is, we check whether farmers choose more water intense crops (cotton) as their water endowment increases.

The first specification is,

$$l_i^k = \alpha + \beta_1 W_i + \boldsymbol{X_i \gamma} + \varepsilon_i \quad (11)$$

Where, l_i^k measures the absolute amount of land planted in the water thirsty crop or alternate crop ($k \in \{c: cotton, m: millet\}$), W_i is as described in equation (9a) and $\boldsymbol{X_i}$ is a vector of controls. We expect to see a negative coefficient on W_i for l_i^c and a positive coefficient on l_i^mas farmers plant less of the primary water consuming crop of the season switching to more water efficient alternate crops. The results can be found in table 4(a) specifications (1) and (2). As expected, we see the coefficient β_1 is positive when the dependent variable is l_i^c. β_1 is positive though insignificant when the dependent variable is l_i^m. This suggests, that farmers tend to plant more land in cotton as the amount of water available increases though they may not vary the amount of millet planted.

Next, we use a similar specification but with a modified dependent variable,

$$c_i^k = \alpha + \beta_1 W_i + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{12}$$

Where all is the same as before, except c_i^k which measures the proportion of planted land dedicated to the water thirsty crop or alternate crop ($k \in \{c\text{: } cotton, m\text{: } millet\}$). The results are shown in table 4a specifications (3) and (4). Here, we see that the relative area in cotton seems not to respond to canal water availability, but that the relative area under millet definitely decreases as the amount of canal water available increases.

Next, we use a final specification,

$$C_i = \alpha + \beta_1 W_i + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{13}$$

Where the dependent variable is the difference between cultivated area normalized (C_i) cotton cropped area (C_i^c) and millet cropped area (C_i^m),

$$\frac{C_i^c - C_i^m}{C_i} \tag{13a}$$

This specification may not tell us which crop is gaining or losing area. But it does confirm that some difference begins to emerge between the two as the amount of water changes. Here we expect a positive coefficient on W_i as farmers plant more land in the water intense crop or less in the water efficient crop. A negative coefficient would suggest that the difference between the area planted in the two crops is being reduced, so that more land (as a proportion of the total cultivated area) is planted with millet or less is planted in cotton. The results are shown in table 4a specification (5). As expected, the coefficient, β_1, is positive and significant. So, the relative amounts of the two crops certainly differ as the amount of canal irrigation water increases.

Finally, we repeat all three sets of specifications above but instead use distance as a proxy for water availability. As before, the first specification is,

$$l_i^k = \alpha + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_3 D_i^3 + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{14}$$

Where the response variable, l_i^k, is a measure of the amount of land in crop k ($k \in \{c\colon cotton, m\colon millet\}$) and D_i^j is a measure of distance along the canal system from the point of origin and $j \in \{primary, secondary, tertiaty\}$. The results are shown in table 4(b) specifications (1) and (2). The area in cotton definitely declines across the three measures of distance (specification (1)). The area in millet seems not to change at the primary and tertiary levels but seems to decline with secondary distance. But note that the response variable is an absolute quantity, not a relative quantity (i.e. it is not cotton relative to millet or the other way around).

The next specification is,

$$c_i^k = \alpha + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_3 D_i^3 + \boldsymbol{X_i \gamma} + \varepsilon_i \qquad (15)$$

Where all is as before except the response variable, c_i^k, which measures the proportion of planted land dedicated to the water thirsty crop or alternate crop ($k \in \{c\colon cotton, m\colon millet\}$). The results are shown in table 4(b) specifications (3) and (4). Now the results seem more definite than in specifications (1) and (2), where the amount of land dedicated to cotton relative to the total available definitely declines across measures of distance and the amount of land dedicated to millet seems to increase (at least in the case of tertiary distance, though it seems not to change over primary and secondary distance).

The final specification we run with distance measures is,

$$C_i = \alpha + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_3 D_i^3 + \boldsymbol{X_i \gamma} + \varepsilon_i \qquad (15)$$

Where all is as before and C_i is as described in equation (13a). The results are shown in table 4(b) specification (5) and concur with specification (5) in table 4(a) i.e. the difference in the amount of land dedicated to cotton and millet declines as the amount of water available declines.

4.3. Fertilizer and Tractor Usage

The third item we explore is the impact of water availability on input usage – fertilizer and tractor. Two sets of specifications are run. The first set is of the form,

$$f_i^k = \alpha + \beta_1 W_i + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{16}$$

Where f_i^k measures bags of fertilizer used, total hours of tractor employed, own tractor hours employed and hired tractor hours employed, $\in \{fertilizer, total\ tractor, own\ tractor, hired\ tractor\}$, W_i is as described in equation (9a) and $\boldsymbol{X_i}$ is a vector of controls. The results are shown in table 5a. The second set of specifications we run is very similar but substitutes the direct measure of water with distances,

$$f_i^k = \alpha + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_3 D_i^3 + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{17}$$

Where D_i^j is a measure of distance along the canal system from the point of origin and $j \in \{primary, secondary, tertiaty\}$. The results are shown in table 5b.

Both sets of results indicate that with higher water availability there is more input usage which is unsurprising. Interestingly, the amount of hired tractor usage increases with water availability.

4.4. Labour Usage

The next input we explore is labour. The first set of specifications has the form,

$$L_i = \alpha + \beta_1 W_i + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{18}$$

Where the response variable, L_i, is a measure of labour used. The results are shown in table 6a. Specification (1) uses total labour used as the response variable, which increases with water availability. Specifications (2) and (3) measure the impact of water availability on own and hired labour usage and again both increase. The final two specifications (4) and (5), regress the ratio of hired labour to the total amount of labour used and the ratio of household labour to the total amount labour (days) used by the farmer during the growing season. These are of interest as they indicate that the amount of hired labour relative to own labour increases significantly as the amount of water available increases.

The second set of specifications is similar to the above,

$$L_i = \alpha + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_3 D_i^3 + \boldsymbol{X_i \gamma} + \varepsilon_i \quad (19)$$

Where now distance measures are used to proxy for water availability. The results are shown in table 6b and concur with those in 6a. Specifically, the amount of labour used declines as the amount of water available declines but the reliance on own labour relative to hired labour increases with water scarcity (i.e. increased distance).

4.5. Groundwater Usage

The final input we consider is groundwater. The first specification we run is,

$$TW_i = \alpha + \beta_1 W_i + \boldsymbol{X_i \gamma} + \varepsilon_i \quad (20)$$

Where the response variable, TW_i, is a binary variable that equals 1 if the farmer owns a water well and pump. The results are shown in table 6a specification (1) which indicates that the likelihood of owning a pump declines with increased water availability. The next set of specifications we run have the form,

$$G_i = \alpha + \beta_1 W_i + \boldsymbol{X_i \gamma} + \varepsilon_i \quad (21)$$

Where G_i is a measure of groundwater usage. We use three distinct measures of groundwater use. In specification (2) it is a measure of actual calculated volume use, in specification (3) it is hours of pump use and in specification (4) it is the cost of running a groundwater pump. All three are valid measures of use. The results are shown in table 7a specifications (2), (3) and (4) and all indicate complimentarity between surface water availability and groundwater use. A final specification we run allows us to explore how much of the total volume of water used by a farmer is groundwater,

$$g_i = \alpha + \beta_1 W_i + \boldsymbol{X_i \gamma} + \varepsilon_i \quad (22)$$

Where g_i is the ratio of groundwater volume applied to the total volume of water applied i.e. canal water and groundwater (acre-inches) by the farmer during the growing season,

$$g_i = \frac{G_i}{(W_i + G_i)} \tag{22a}$$

Where W_i is as described in equation (9a) and G_i is the volume of groundwater used by a farmer. The results are shown in table 7a specification (5) and suggest that as the amount of surface water availability increases the amount of groundwater used as a proportion of total water declines.

A similar set of specifications is run using distance measures as proxies for water availability. The specifications are,

$$TW_i = \alpha + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_3 D_i^3 + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{23}$$

And,

$$G_i = \alpha + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_3 D_i^3 + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{24}$$

And,

$$g_i = \alpha + \beta_1 D_i^1 + \beta_2 D_i^2 + \beta_3 D_i^3 + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{25}$$

Where all is as before except that instead of W_i the three measures of distance are being used, D_i^j for $j \in \{primary, secondary, tertiaty\}$. The results are presented in table 7b. The results are not as powerful as in the case of the direct volumetric measure of water and do not present a clear picture of what is happening.

Finally, we explore the role of surface water and local groundwater quality in groundwater usage more carefully. To this end we run the following specification,

$$g_i = \alpha + \beta_1 W_i + \beta_2 Q_i + \beta_3 {W_i}^2 + \beta_4 {Q_i}^2 + \beta_5 W_i * Q_i + \boldsymbol{X_i \gamma} + \varepsilon_i \tag{26}$$

Where g_i is as defined in equation (22a), W_i is as defined in equation (9a) and Q_i is a measure of local groundwater quality (electrical conductivity measured in micro-seimens). The specification contains second order polynomial terms for surface water use and groundwater quality along with an interaction term of the two. The results are shown in table 7c. We build up tot he full specification, where specification (1) does not contain the quadratic terms or the interaction and specification (2) does not contain the interaction term. Specification (3) is the full specification containing quadratic terms and the interaction term. The full specification (3) indicates that the relation between groundwater usage and surface water is nonlinear and has a convex form. This implies that as the surface water availability increases farmers are more willing to use groundwater. Specification (3) also indicates that groundwater use is a nonlinear function of local groundwater quality (concave in form). Thus, farmers may be levelling-off the amount of groundwater they use as the salinity gets higher and higher. Finally, the interaction term suggests that as the more surface water is available but groundwater salinity increases, farmers use less groundwater.

5 Discussion

Our first result, that of reduced cultivated area with reduction in water availability fits in with a stylized fact in agricultural and development economics called inverse productivity (IP). Three potential causes for IP have been put forth. The first cause is due to imperfect labour markets where small farms employ more own labour since it is not absorbed in the labour market (Sen (1966), Feder (1985), Barret (1996)). The second cause, soil quality, explains IP in the sense that farmers use their best lands (better levelled, better access to water, better soil nutrients and balance) first thus increasing productivity (Benjamin (1995), Bhalla and Roy (1988)). Finally, measurement error in measurement of farm size may cause incorrect inference about the productivity of a farm (Lamb (2003)). We are not in a position to be able to test these three possibilities, though we can certainly get indications for the first cause. What we can do is test for increased reliance on hired labour as the amount of planted land increases. To this end we use two stage least squares, using distance and water delivery as instruments for planted area. The first stage is,

$$l_i = \alpha + \beta_1 Z_i + \varepsilon_i \tag{20}$$

Where l_i is a measure of cultivated land and Z_i is our instrument (distance along the canal system). The second stage,

$$h_i = \alpha + \beta_1 l_i^{IV} + \varepsilon_i \tag{21}$$

Where h_i is hired labour used per acre of cultivated land, l_i^{IV} is the residual from the first stage. The results from this are presented in table 8. We find that the amount of hired labour (measured in terms of hours) tends to increase with the area cultivated. This suggests that we may be seeing IP due to a higher reliance on outside labour by farmers who cultivate more area.

The other major finding is that farmers change their crop mix as water availability declines. We used multiple specifications to test this and consistently saw a shift to millet with reduced water availability (or a shift to cotton with increased water availability). Millet is a coarse grain that is often consumed on-farm rather than sold on the market (both for human consumption and as fodder). It is definitely a more water efficient crop well suited to low moisture environments and farmers with lower water availability switch to it. To be clear, the word switch does not imply a binary move to one crop or the other. Rather, we see that of the land that farmers cultivate, more (less) is dedicated to cotton (millet) as the amount of water available increases (decreases).

Finally, input use is modulated by water availability. Reliance on more outside (i.e. not own household) tractor and labour usage increases with water availability. This might just be reflective o the first order finding that the amount of land a farmer plants increases with water availability. Thus, as the scale of cultivation increases a farmer starts to rely on outside sources of input – which is not surprising.

Groundwater input provides the most interesting case. Groundwater use is certainly modulated by availability of surface irrigation water. As we expected, the likelihood of owning a tubewell pump declines the more water is available which suggests that farmers are less willing to invest in this capital and fuel intensive technology if their surface water environment is relatively comfortable. In terms of actual use of groundwater, there is certainly complimentarity with surface water. However, the story is somewhat more complex since there is in fact a non-linear relationship between groundwater use and surface water delivered and the fact that groundwater is modulated by its local quality (salinity). The results indicate that groundwater use and surface water availability have a convex relation. This implies that farmers are actually willing to use more groundwater as their surface water availability increases. This ties in with the second finding about groundwater quality. Clearly, groundwater salinity limits how much groundwater can be used. With more surface water available farmers are able to mix more saline groundwater in to augment their total water availability. With greater amounts of surface water the salinity of groundwater is diluted. Groundwater quality itself has a non-linear and concave relation with groundwater use. This fact makes sense too. As the concentration of salt in the groundwater increases, the amount farmers are willing to use levels off. Finally, the results also indicate that as the amount of surface water increases along with groundwater salinity the share of groundwater used declines. All of this definitely suggests that farmers are quite cognizant of their groundwater input quality and are engaging in optimally mixing surface and ground sources to maximize their net revenue.

6 Conclusions

Surface water availability has a real impact on farmers. Perhaps the two biggest impacts of water availability on farmers is the amount of land they can bring under cultivation and their cropping mix. The amount of land under cultivation is impacted quite strongly by the quantity of surface water available to farmers, where farmers with less surface water cultivate less land. Additionally, farmers also manipulate their cropping mix in response to water availability, switching from more water intense to less water intense crops as water availability declines. Related to this is a change in input use patterns. The shift is obvious – with a reduction in land cultivated and a switch to hardy less water intense crops the need for capital inputs declines (as was shown). However, one input has a more complex usage pattern. At first blush, the amount of groundwater used by farmers certainly increases with surface water availability, indicating its complimentarity. However, groundwater use is also modulated by its quality (salinity). Investigation into groundwater use indicated that: (a) groundwater use and surface water availability have a non-linear (convex) relation; (b) groundwater use and groundwater quality also have a non-linear (concave) relation; and (c) a concurrent increase in surface water availability and groundwater salinity reduces the overall quantity of groundwater used. All of this suggests that farmers are engaging in optimal mixing of surface and groundwater. Groundwater has to be mixed with surface water if it is to be a productive input since it has a distinct quality issue (salinity).

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Figure 1.

Farmer net revenue (Rupees) and different measures of water availability.

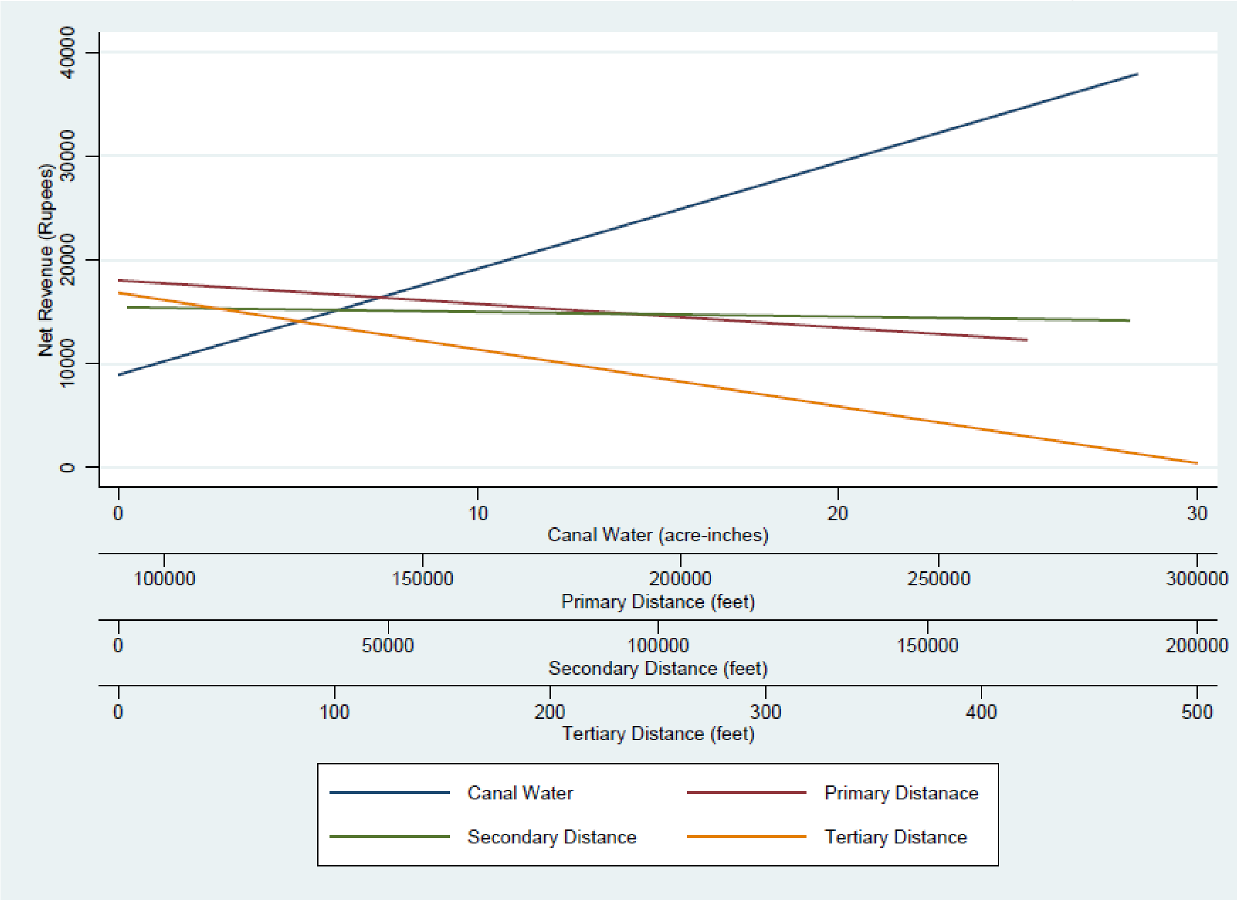

Figure 2a.
A simplified schematic of the Indus Basin Irrigation system

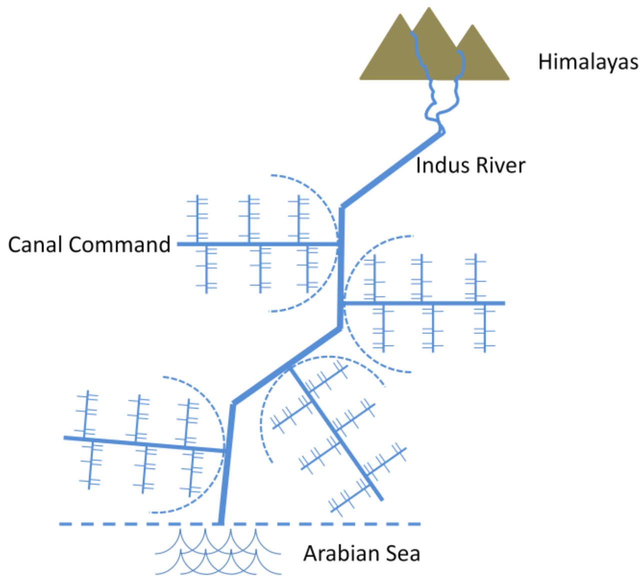

Figure 2b.
A simplified diagram of the three levels of a canal command. Blue arrow shows path water takes to get to farmer (red dot) from source (blue dot).

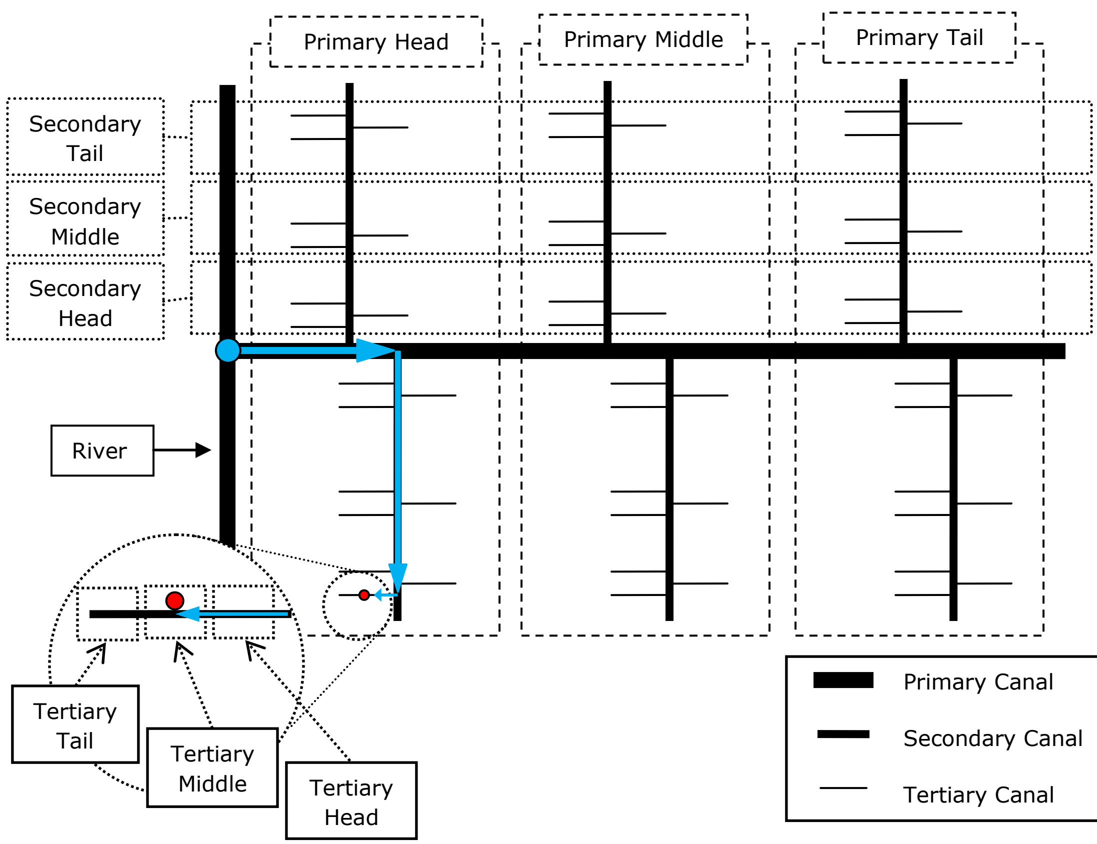

Figure 3a.
A typical Hakra Branch Canal distributory channel (secondary canal) with direction of flow indicated.

Figure 3b.
A typical outlet structure on a Hakra Branch Canal distributory. Outlet draws water from the distributory channel.

Figure 4.

Outlet structures are the institutional boundary between farmers and the irrigation department (adapted from Akram (2013).

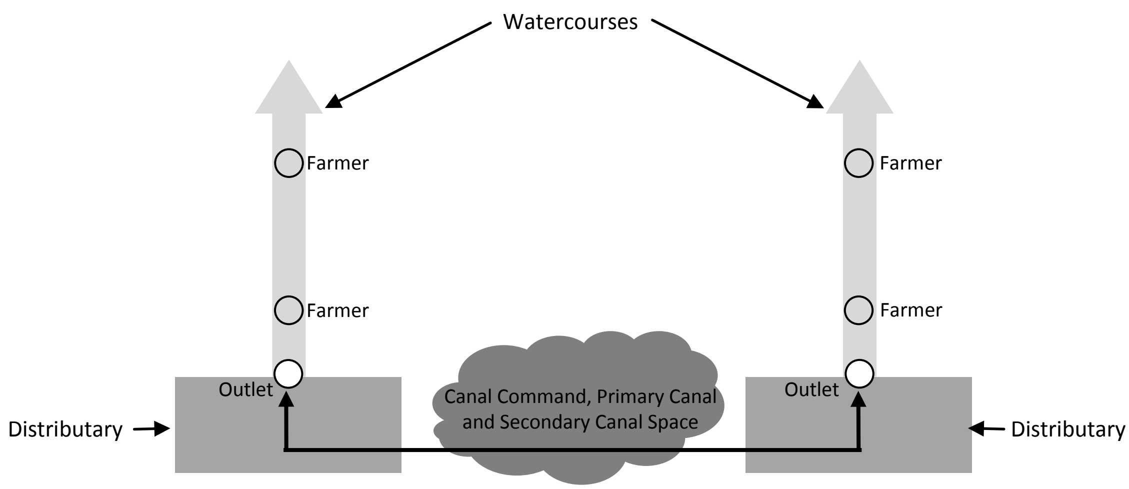

Table 1. Relation between net revenue, canal water and distance

VARIABLES	(1) NR/ Acre	(2) NR/ Acre
CanalWater/Acre	1,001***	
	(253.2)	
PrimaryDistance		-0.0257
		(0.0161)
SecondaryDistance		-0.0548**
		(0.0249)
TertiaryDistance		-24.51**
		(11.62)
Controls	*Yes*	*Yes*
Constant	5,586	-3,878
	(8,464)	(8,305)
Observations	332	334
R-squared	0.131	0.173

Specification (1) regresses net revenue per acre on distance along the primary canal, secondary canal and tertiary canal segment that a farmer is located on. Specification (2) regresses net revenue per acre on measured canal water per acre. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 2. Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Number of members in household?	363	9.446281	5.639664	2	40
Number of Adults (18+ years)?	363	6.044077	3.650965	2	25
Number of household members that work?	363	2.479339	1.649205	0	15
How many years of formal education has the respondent had?	363	3.336088	2.118713	0	8
How many a year of formal education has the female head of HH had?	363	1.487603	2.123724	0	8
Have sons received any formal education?	363	0.9586777	0.1993093	0	1
Have daughters received any formal education?	363	0.9449036	0.2284833	0	1
How many years have you been managing farms?	363	18.44353	10.85637	1	64
How many years have you been involved in agriculture?	363	28.66391	12.44091	1	60
Have you had any contact with agricultural extension services?	363	0.4517906	0.4983573	0	1
Are you involved in livestock production?	363	0.9283747	0.2582225	0	1
Do you have formal sector loans?	363	0.2176309	0.4132046	0	1
Do you determine what to grow in the winter season based on summer season outcomes?	363	0.4738292	0.5000038	0	1
Positional preference: Main Hakra Canal?	363	1.146006	0.361327	1	3
Positional preference: Your Distributory?	363	1.272727	0.4701005	1	3
Positional preference: Your Watercourse?	363	1.37741	0.6247536	1	3
This land (1) is inherited or bought?	363	1.980716	0.1377103	1	2
If bought then purchasing amount (1)?	7	424285.7	463496	20000	1260000
This land (2) is inherited or bought?	12	1.916667	0.2886751	1	2
If bought then purchasing amount (2)?	1	140000	.	140000	140000
This land (3) is inherited or bought?	7	2	0	2	2
If bought then purchasing amount (3)?	0				
This land (4) is inherited or bought?	3	2	0	2	2
If bought then purchasing amount (4)?	0				
Planted Area (acres)	363	10.98409	11.06813	0.75	102
Land Value (Rs.)	363	6211019	7006191	0	91200000

Table 3a. Planted Area and Canal Water Availability (Volumetric Measure)

VARIABLES	(1) Planted Area	(2) Planted ToTotalArea Ratio
CanalWater/Acre	0.213***	0.0184***
	(0.0328)	(0.00228)
Controls	*Yes*	*Yes*
Constant	-3.565	0.763***
	(2.246)	(0.111)
Observations	334	334
R-squared	0.875	0.277

PlantedArea is a measure of the actively cultivated area a farmer managed during the growing season. PlantedToTotalAreaRatio is the ratio of planted area to total available area (the total area available to potentially cultivate) for a farmer during the growing season. CanalWater/Acre is an in-season volumetric measure (acre-inches) of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 3b. Planted Area and Canal Water Availability (Distance as Proxy for Availability)

VARIABLES	(1) Planted Area	(2) Planted ToTotalArea Ratio
PrimaryDistance	-1.52e-05***	-1.08e-06***
	(3.68e-06)	(2.09e-07)
SecondaryDistance	-2.06e-05***	-1.77e-06***
	(4.50e-06)	(3.04e-07)
TertiaryDistance	-0.0113***	-0.000849***
	(0.00311)	(0.000197)
Controls	*Yes*	*Yes*
Constant	0.999	1.116***
	(1.862)	(0.101)
Observations	332	332
R-squared	0.885	0.338

PlantedArea is a measure of the actively cultivated area a farmer managed during the growing season. PlantedToTotalAreaRatio is the ratio of planted area to total available area (the total area available to potentially cultivate) for a farmer during the growing season. PrimaryDistance, SecondaryDistance and TrertiaryDistance are, respectively, distance along the primary canal, secondary canal and tertiary canal segment that a farmer is located on. These distances represent a proxy measure of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 4a. Area Planted in Cotton and Millet and Canal Water Availability (Volumetric Measure)

VARIABLES	(1) AreaIn Cotton	(2) AreaIn Millet	(3) CottonTo TotalArea Ratio	(4) MilletTo TotalArea Ratio	(5) Diff CottonMillet Ratio
CanalWater/Acre	0.177***	0.0270	0.00429	-0.00416*	0.00845*
	(0.0398)	(0.0213)	(0.00274)	(0.00244)	(0.00495)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	-3.077	-0.0117	0.849***	0.203**	0.647***
	(2.226)	(0.743)	(0.0854)	(0.0815)	(0.161)
Observations	334	334	334	334	334
R-squared	0.853	0.228	0.135	0.124	0.135

AreaInCotton is a measure of the absolute amount of area planted in cotton (acres) by a farmer during the growing season. AreaInMillet is a measure of the absolute amount of area planted in millet (acres) by a farmer during the growing season. CottonToTotalAreaRatio is the ratio of the area planted in cotton (acres) to the total area available (acres) to a farmer during the growing season. MilletToTotalAreaRatio is the ratio of the area planted in millet (acres) to the total area available (acres) to a farmer during the growing season. DiffCottonMilletRatio is the difference between CottonToTotalAreaRatio and MilletToTotalAreaRatio for a farmer during the growing season. CanalWater/Acre is an in-season volumetric measure (acre-inches) of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 4b. Area Planted in Cotton and Millet and Canal Water Availability (Distance as Proxy for Availability)

VARIABLES	(1) AreaIn Cotton	(2) AreaIn Millet	(3) CottonTo TotalArea Ratio	(4) MilletTo TotalArea Ratio	(5) Diff CottonMillet Ratio
PrimaryDistance	-1.74e-05***	3.35e-07	-4.29e-07**	2.22e-07	-6.52e-07*
	(3.38e-06)	(1.86e-06)	(1.87e-07)	(1.83e-07)	(3.47e-07)
SecondaryDistance	-1.81e-05***	-5.64e-06**	-3.58e-07	-5.60e-08	-3.02e-07
	(4.95e-06)	(2.56e-06)	(3.43e-07)	(3.48e-07)	(6.68e-07)
TertiaryDistance	-0.0143***	0.00182	-0.000642***	0.000383**	-0.00102***
	(0.00299)	(0.00127)	(0.000167)	(0.000156)	(0.000299)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	1.764	0.00683	1.000***	0.107	0.893***
	(1.741)	(0.705)	(0.0899)	(0.0859)	(0.170)
Observations	332	332	332	332	332
R-squared	0.874	0.242	0.185	0.139	0.169

AreaInCotton is a measure of the absolute amount of area planted in cotton (acres) by a farmer during the growing season. AreaInMillet is a measure of the absolute amount of area planted in millet (acres) by a farmer during the growing season. CottonToTotalAreaRatio is the ratio of the area planted in cotton (acres) to the total area available (acres) to a farmer during the growing season. MilletToTotalAreaRatio is the ratio of the area planted in millet (acres) to the total area available (acres) to a farmer during the growing season. DiffCottonMilletRatio is the difference between CottonToTotalAreaRatio and MilletToTotalAreaRatio for a farmer during the growing season. PrimaryDistance, SecondaryDistance and TrertiaryDistance are, respectively, distance along the primary canal, secondary canal and tertiary canal segment that a farmer is located on. These distances represent a proxy measure of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 5a. Fertilizer, Tractor and Canal Water Availability (Volumetric Measure)

VARIABLES	(1) Fertilizer/ Acre	(2) TotalTractor Hours/ Acre	(3) OwnTractor Hours/ Acre	(4) HiredTractor Hours/ Acre
CanalWater/Acre	0.0604***	0.0629**	0.0103	0.0526*
	(0.0134)	(0.0307)	(0.00760)	(0.0313)
Controls	*Yes*	*Yes*	*Yes*	*Yes*
Constant	1.541***	2.035***	-0.361*	2.397***
	(0.429)	(0.616)	(0.185)	(0.617)
Observations	334	334	334	334
R-squared	0.208	0.142	0.096	0.144

Fertilizer/Acre is a measure of fertilizer applied (bags) by a farmer during the growing season. TotalTractorHours/Acre is a measure of all tractor usage (hours) by a farmer during the growing season. OwnTractorHours/Acre is a measure of farmer's own tractor usage (hours) during the growing season. HiredTractorHours/Acre is a measure of hired tractor usage (hours) by the farmer during the growing season. CanalWater/Acre is an in-season volumetric measure (acre-inches) of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 5b. Fertilizer, Tractor and Canal Water Availability (Distance as Proxy for Availability)

VARIABLES	(1) Fertilizer/ Acre	(2) TotalTractor Hours/ Acre	(3) OwnTractor Hours/ Acre	(4) HiredTractor Hours/ Acre
PrimaryDistance	-4.38e-06***	4.39e-06*	-4.93e-07	4.88e-06**
	(1.06e-06)	(2.36e-06)	(6.75e-07)	(2.31e-06)
SecondaryDistance	-4.53e-06***	-7.44e-06***	-7.21e-07	-6.72e-06***
	(1.62e-06)	(2.42e-06)	(1.02e-06)	(2.46e-06)
TertiaryDistance	-0.00264***	-0.00192	0.000301	-0.00222
	(0.000894)	(0.00135)	(0.000434)	(0.00139)
Controls	*Yes*	*Yes*	*Yes*	*Yes*
Constant	2.764***	2.154**	-0.253	2.406***
	(0.458)	(0.862)	(0.204)	(0.857)
Observations	332	332	332	332
R-squared	0.241	0.160	0.095	0.168

Fertilizer/Acre is a measure of fertilizer applied (bags) by a farmer during the growing season. TotalTractorHours/Acre is a measure of all tractor usage (hours) by a farmer during the growing season. OwnTractorHours/Acre is a measure of farmer's own tractor usage (hours) during the growing season. HiredTractorHours/Acre is a measure of hired tractor usage (hours) by the farmer during the growing season. PrimaryDistance, SecondaryDistance and TrertiaryDistance are, respectively, distance along the primary canal, secondary canal and tertiary canal segment that a farmer is located on. These distances represent a proxy measure of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 6a. Labour and Canal Water Availability (Volumetric Measure)

VARIABLES	(1) Total Labour /Acre	(2) Own Labour /Acre	(3) Hired Labour /Acre	(4) HiredTo TotalLabour Ratio	(5) OwnTo TotalLabour Ratio
CanalWater/Acre	2.217***	0.882***	1.335***	0.00800**	-0.00800**
	(0.602)	(0.338)	(0.466)	(0.00309)	(0.00309)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	60.83***	36.44***	24.39**	0.323**	0.677***
	(19.05)	(12.15)	(11.80)	(0.132)	(0.132)
Observations	334	334	334	334	334
R-squared	0.359	0.288	0.253	0.136	0.136

TotalLabour/Acre is a measure of the total labour used (days) by the farmer during the growing season. OwnLabour/Acre is a measure of the household labour used (days) by the farmer during the growing season. HiredLabour/Acre is a measure of the hired labour used (days) by the farmer during the growing season. HiredToTotalLabourRatio is the ratio of hired labour (days) to the total number of labour (days) used by the farmer during the growing season. OwnToTotalLabourRatio is the ratio of household labour (days) to the total number of labour (days) used by the farmer during the growing season. CanalWater/Acre is an in-season volumetric measure (acre-inches) of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 6b. Labour and Canal Water Availability (Distance as Proxy for Availability)

VARIABLES	(1) TotalLabour /Acre	(2) OwnLabour /Acre	(3) HiredLabour /Acre	(4) HiredTo TotalLabour Ratio	(5) OwnTo TotalLabour Ratio
PrimaryDistance	-8.31e-05	7.03e-06	-9.01e-05***	-9.21e-07***	9.21e-07***
	(5.34e-05)	(3.29e-05)	(3.31e-05)	(2.55e-07)	(2.55e-07)
SecondaryDistance	-0.000216***	-6.55e-05*	-0.000151***	-9.80e-07**	9.80e-07**
	(5.60e-05)	(3.58e-05)	(4.00e-05)	(4.29e-07)	(4.29e-07)
TertiaryDistance	0.00735	-0.0378	0.0452	0.000137	-0.000137
	(0.0441)	(0.0276)	(0.0374)	(0.000266)	(0.000266)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	87.99***	45.30***	42.69***	0.500***	0.500***
	(18.58)	(12.76)	(12.16)	(0.133)	(0.133)
Observations	332	332	332	332	332
R-squared	0.349	0.285	0.263	0.162	0.162

TotalLabour/Acre is a measure of the total labour used (days) by the farmer during the growing season. OwnLabour/Acre is a measure of the household labour used (days) by the farmer during the growing season. HiredLabour/Acre is a measure of the hired labour used (days) by the farmer during the growing season. HiredToTotalLabourRatio is the ratio of hired labour (days) to the total number of labour (days) used by the farmer during the growing season. OwnToTotalLabourRatio is the ratio of household labour (days) to the total number of labour (days) used by the farmer during the growing season. PrimaryDistance, SecondaryDistance and TrertiaryDistance are, respectively, distance along the primary canal, secondary canal and tertiary canal segment that a farmer is located on. These distances represent a proxy measure of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 7a. Groundwater and Canal Water Availability (Volumetric Measure)

VARIABLES	(1) Owns TubeWell	(2) Groundwater Volume /Acre	(3) Groundwater HoursOf Pumping /Acre	(4) Groundwater Cost /Acre	(5) Groundwater To TotalWater Ratio
CanalWater/Acre	-0.0139**	70.12	0.371*	129.4**	-0.0140***
	(0.00553)	(78.72)	(0.189)	(50.56)	(0.00209)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	0.045***	-359.1	10.61	4,320***	0.124**
	(0.201)	(2,008)	(7.291)	(1,558)	(0.0559)
Observations	334	334	334	334	334
R-squared	0.152	0.041	0.056	0.145	0.190

OwnsTubewell = 1 if the farmer owns his own water pumping machinery and a water borehole on-site. GroundwaterVolume/Acre is a measure of groundwater volume applied (acre-inches) by the farmer during the growing season. GroundwaterHoursOfPumping/Acre is a measure of the time the groundwater pump was operated (hours) by the farmer during the growing season. GroundwaterCost/Acre is a measure of the cost of groundwater applied (Rupees) by the farmer during the growing season. GroundwaterToTotalWaterRatio is the ratio of groundwater volume applied (acre-inches) to the total volume of water applied i.e. canal water and groundwater (acre-inches) by the farmer during the growing season. CanalWater/Acre is an in-season volumetric measure (acre-inches) of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 7b. Groundwater and Canal Water Availability (Distance as Proxy for Availability)

VARIABLES	(1) Owns Tubewell	(2) Groundwater Volume /Acre	(3) Groundwater HoursOf Pumping /Acre	(4) Groundwater Cost /Acre	(5) Groundwater To TotalWater Ratio
PrimaryDistance	-6.13e-07	-0.00650	-2.70e-05	0.00497	1.85e-07
	(4.11e-07)	(0.00682)	(2.19e-05)	(0.00390)	(1.75e-07)
SecondaryDistance	1.44e-07	-0.0123	-8.38e-05**	0.00915	5.14e-07
	(7.11e-07)	(0.0144)	(4.21e-05)	(0.00633)	(3.52e-07)
TertiaryDistance	0.000613*	2.919	0.0136	0.602	9.53e-05
	(0.000368)	(5.214)	(0.0175)	(2.686)	(0.000113)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	0.115***	787.0	16.28*	4,642***	-0.0169
	(0.198)	(2,289)	(8.331)	(1,660)	(0.0625)
Observations	332	332	332	332	332
R-squared	0.146	0.044	0.069	0.139	0.091

OwnsTubewell = 1 if the farmer owns his own water pumping machinery and a water borehole on-site. GroundwaterVolume/Acre is a measure of groundwater volume applied (acre-inches) by the farmer during the growing season. GroundwaterHoursOfPumping/Acre is a measure of the time the groundwater pump was operated (hours) by the farmer during the growing season. GroundwaterCost/Acre is a measure of the cost of groundwater applied (Rupees) by the farmer during the growing season. GroundwaterToTotalWaterRatio is the ratio of groundwater volume applied (acre-inches) to the total volume of water applied i.e. canal water andS groundwater (acre-inches) by the farmer during the growing season. PrimaryDistance, SecondaryDistance and TrertiaryDistance are, respectively, distance along the primary canal, secondary canal and tertiary canal segment that a farmer is located on. These distances represent a proxy measure of canal water availability. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 7c. Groundwater and Canal Water Availability (Volumetric Measure)

VARIABLES	(1) Groundwater To TotalWater Ratio	(2) Groundwater To TotalWater Ratio	(3) Groundwater To TotalWater Ratio
CanalWater/Acre	-0.0140***	-0.0442***	-0.0337***
	(0.00209)	(0.00733)	(0.00790)
(CanalWater/Acre)^2		0.00152***	0.00153***
		(0.000346)	(0.000322)
GroundwaterSalinity	1.10e-05	8.36e-05**	0.000117***
	(1.08e-05)	(4.00e-05)	(4.53e-05)
(GroundwaterSalinity)^2		-1.31e-08**	-1.51e-08**
		(6.64e-09)	(6.86e-09)
CanalWater/Acre x *GroundwaterSalinity*			-4.14e-06*
			(2.19e-06)
Controls	*Yes*	*Yes*	*Yes*
Constant	0.124**	0.168**	0.0872
	(0.0559)	(0.0745)	(0.0865)
Observations	334	334	334
R-squared	0.190	0.273	0.282

GroundwaterToTotalWaterRatio is the ratio of groundwater volume applied (acre-inches) to the total volume of water applied i.e. canal water an groundwater (acre-inches) by the farmer during the growing season. CanalWater/Acre is an in-season volumetric measure (acre-inches) of canal water availability. GroundwaterSalinity is a measure of local groundwater salinity levels measured in units of electrical conductivity. All specifications include a vector of controls. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Table 8. Impact of Planted Area on Hired Labour (IV)

	(1)
VARIABLES	HiredLabour/Acre
PlantedArea	4.806***
	(1.667)
Constant	-19.31
	(12.75)
Observations	334
R-squared	...

HiredLabour/Acre is a measure of the hired labour used (days) by the farmer during the growing season. PlantedArea is a measure of the actively cultivated area a farmer managed during the growing season. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.