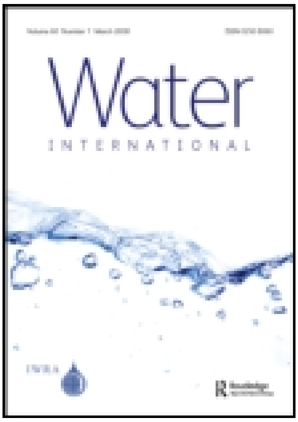

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Is a surface-water market physically feasible in Pakistan's Indus Basin Irrigation System?

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Is a surface-water market physically feasible in Pakistan's Indus Basin Irrigation System?

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This paper argues that a water market is physically feasible in the existing reality of Pakistan's Indus Basin Irrigation System at the watercourse and distributary levels. The paper starts by describing the existing system and contrasts it with ideal economic management of surface water. It then lays out the degree and extent of modification to outlet structures that would be needed to enable trading based on structure type and the scale of the water-trading region, along with a first glance at the relative costs of those modifications. The ongoing decentralization of irrigation management should support water-trading efforts.

Keywords: Pakistan; Indus Basin Irrigation System; water market; outlet modification

Introduction

Economists suggest that water markets are the preferred mechanism for water allocation amongst the users of the resource (Easter, Rosegrant, & Dinar, 1998; Rosegrant & Binswanger, 1994). When water is traded (rather than allotted in a fixed manner), the welfare of the trading entities is improved, since those users who extract the most value from the available water will tend to use it, while those that give up that water will be compensated for the exchange. However, creating a market is difficult, as it requires creating clear property rights, monitoring and enforcement mechanisms, and capable human resources; accounting for quantity externalities (especially third-party impacts in terms of discharge changes); and taking quality externalities into account (Easter et al., 1998; Howe, Schurmeier, & Shaw, 1986). Moreover, benefits need to surpass transaction costs (Challen, 2000; Colby, 1990). Given these challenges, formal water markets tend to be rare.

While there are few formal water markets globally, informal markets are common, particularly in South Asia, and including Pakistan. Informal water markets are found in all the provinces of Pakistan, and they are most prevalent in canal-irrigated areas of Punjab (Meinzen-Dick, 1996). Factors leading to informal water marketing in Pakistan include poor-quality groundwater, available-but-unreliable canal irrigation, and medium-sized land holdings. Groundwater sellers tend to reap the largest economic benefits, whereas purchasers indicate the lack of reliability of supplies. It is important to note that these informal markets occur at a very local level in the irrigation system, i.e. from farmer to farmer within a watercourse (Meinzen-Dick, 1996).

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For formal water markets to function, state recognition of private water rights, and especially water rights that are separable from land, is important, as is state regulation of transfers (Easter et al., 1998). Market transfers directly compensate those who engage in the transfers, but generally do not take into account the water claims of others who may be affected, unless specific mechanisms for the compensation of third parties have been introduced (Easter et al., 1998).

While economists focus on market-based solutions, engineers, who continue to dominate the irrigation water allocation profession, aim at minimizing the difference between crop water demands and irrigation supplies through changes in infrastructural means and (re)allocation of canal supplies. Moreover, engineers and economists seldom speak the same language, or to each other.

This paper aims at partly bridging this gap; i.e. it discusses the potential and limits of water marketing in the context of the Indus Basin Irrigation System (IBIS), which has been designed and is managed entirely by engineers.

Given the large size (18 million hectares of irrigated area) and complex physical environment of the IBIS, any introduction of a water market into the system would need to be carefully attuned to this physical reality. For example, a spot market (i.e. where a transaction yields immediate delivery) for very small quantities of water could be achieved through an automated piped network that is metered for volume flow. But such a market would not be feasible in Pakistan's IBIS in terms of cost and existing human resource capability with present technologies. This paper will describe the feasibility of a surface irrigation water market at the watercourse scale, i.e. between watercourses (with extension to distributaries). This is a scale that does not immediately seem amenable to trade; but, as this paper shows, it is feasible.

The focus of the paper is on trading of irrigation water amongst agricultural users; it does not speak to inter-sectoral trading such as between agriculture and urban areas or between agriculture and industry, where most other formal, permanent trades have taken place (Brewer, Glennon, Ker, & Libecap, 2006). To date, most urban and industrial areas in Pakistan continue to rely on groundwater to meet water demand, especially in Punjab Province; and this demand has been estimated at only 5.3 km^3, a small fraction of irrigation water demands (GOP, 2002). It is important to note that in parts of the IBIS, conjunctive use of surface water and groundwater are common, which increases interdependencies among users. For example, if farmers substitute traded surface water with additional groundwater pumping, pumping costs and changes in groundwater quality could affect other users of the groundwater source (Knapp, Weinberg, Howitt, & Posnikoff, 2003).

This paper presents a first cut at thinking through some fundamental conditions for a market to emerge in the Pakistani irrigation system, namely the physical feasibility of trading on the back of the existing infrastructure. It provides a starting point for economists and irrigation engineers to begin thinking about the realities of an irrigation water market in Pakistan.

Description of the Indus Basin Irrigation System

This section briefly describes Pakistan's agricultural and irrigation systems. In 2010, agriculture contributed 21% of the gross domestic product, down from 51% in the 1950s (World Bank, 2013). In addition, an estimated 44% of the labour force is engaged in agriculture, down from 68% in the 1950s (Khan, 2005).

Irrigated agriculture is critical to Pakistan's agricultural productivity and food security, owing to Pakistan's arid and semi-arid climate. Agricultural consumption dominates water use in Pakistan: while domestic and industrial consumption account for close to 2% each, agriculture accounts for a staggering 97% of total water usage (Gleick, 2000). Agricultural water use in Pakistan is thus well above the global average of about 70% (Prinz & Singh, 2000).

The IBIS is a continuous-flow, fixed-rotation system with a significant network of infrastructure regulated by 2 major multi-purpose storage reservoirs (the Mangla and the 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). The water of the Indus flows onto the plains through regulatory structures known as rim stations. About 173 km^3, the bulk of the water available to Pakistan, passes through the rim stations (Riebsame et al., 1995). The total live capacity of the 2 major reservoirs as well as the smaller Chashma was close to 20 km^3 originally (National Water Policy, 2004). However, siltation has reduced this to 15.7 km^3 as of 2002. In total, the storage capacity available on the Indus River system is about 30 days. This is low compared to other large river systems. For example, in neighbouring India, the Krishna and Narmada River basins possess over five times the storage capacity of the Indus (Briscoe & Qamar, 2006). At the high end, the Colorado and Murray-Darling River basins each have around 900 days of storage.

Water is diverted through 43,561 km of canals, 18,884 km of seepage-cum-storm water drains and 12,612 km of tile drains in the Indus Plain, mostly in the two key agricultural production areas of Punjab and Sindh, with a total designed discharge of 7376 m^3/s (National Water Policy, 2004). It is estimated that “the irrigation system commands an area of 18.2 million ha” (Latif, 2007).

There are 45 main canal commands (or canal systems), and each can be broken down into three distinct levels: primary or main canals; secondary canals or water channels (also referred to as distributaries and minors); and 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. There are close to 107,000 outlets (National Water Policy, 2004). Outlet structures tend to be fixed and may be proportional or non-proportional in nature (this is discussed in detail ahead).

Annual average irrigation diversions are 128 km^3 (i.e. significantly less than the total average discharge through the system, a consequence of the low storage capacity), but these surface-water supplies are insufficient to meet irrigation requirements, leaving farmers to supplement the shortfall (about 40%) with groundwater pumping and rainfall (Ullah, Habib, & Muhammad, 2001). While canal diversions would theoretically be sufficient to meet the total estimated annual irrigation water demand of 100 km^3 (Randhawa, 2002), in Punjab, for example, 30–60% of the canal water leaks into groundwater (Kahlown & Kemper, 2004), requiring supplementary groundwater pumping from this leaked water.

Groundwater pumping proliferated in Pakistan starting in the 1960s. Estimates put the number of tubewells at close to 600,000 (Briscoe & Qamar, 2005). It seems likely that the proportion of water supplied by the canal system may shrink further, especially as the demand for agricultural water is predicted to grow considerably. Pakistan’s National Water Policy projects that water demand will grow from the current 100 km^3/y to about 120 km^3/y by 2025 (National Water Policy, 2004). Given that past compensation for water shortfalls was achieved through groundwater development, it seems very likely that future demand will also see a significant amount of groundwater usage. However, the groundwater in the system is becoming progressively more saline, with long-term adverse consequences for soil health (Van Steenbergen & Gohar, 2005).

Irrigation water management in Pakistan

The potential for surface-water marketing for agriculture

Agriculture, the primary user of Pakistan's water resources, operates in a "water short environment" (Latif, 2007). Therefore, water allocation should strive to maximize the efficiency of this scarce resource. Economic theory suggests that water be allocated to agricultural users based on their valuation of water: those users who place a high value on water should be allocated more of it (the equimarginal principle). Achieving a market for surface irrigation water is a non-trivial undertaking, in terms of both the institutions involved and the physical complexity of trading and its consequences. Many economists have argued the case for the introduction of market-based water allocation in the water sector and in agricultural water allocation specifically (see e.g. Easter et al., 1998; Howe et al., 1986; Rosegrant & Binswanger, 1994), while also emphasizing the challenges involved.

In Pakistan's surface irrigation system we find a very specific water-allocation scenario: an irrigation network where water use is almost entirely consumptive (as illustrated in Figure 1). The assumption of consumptive use is valid because, as stated before, much of Pakistani agriculture is water short, and farmers make up the deficit by extracting groundwater. Therefore, return flows to the system are small.

Figure 1 shows a canal reach, where water flows from a source and is diverted to farmers along the way. For instance, water allocated at the source node for Farmer 2 (i.e. v_2) will not arrive at a demand node totally unattenuated; i.e. $v_2 \geq w_2(z_2,v_2)$. Water that actually makes it to Farmer 2 (w_2) is a function of the original allocation (v_2) and an efficiency term (z_2). (This merely demonstrates the idea of loss; of course if any user along the system adjusted their intake, it would impact downstream users' uptakes.)

Economic theory suggests that a price be set at the point where the marginal net benefits of water are equalized across farmers so that farmers can buy the optimal quantity of water in a market – or, equivalently, that water is allocated by a "central planner" so that the marginal net benefits of water are equalized across users (see Howe et al., 1986). Economic theory also suggests that the losses in the system be accounted for (Chakravorty & Roumasset, 1991). Thus, the marginal net benefits of water must be equalized across users, with delivery losses in the canal system having been accounted for. Also, surface-water supplies often interact with groundwater, which further complicates the picture (Tsur, 1997).

The following (simple) model provides a basic illustration of the efficiency conditions of surface-water allocation. It is meant to compactly demonstrate economic efficiency and is not a comprehensive theoretical treatment. Consider

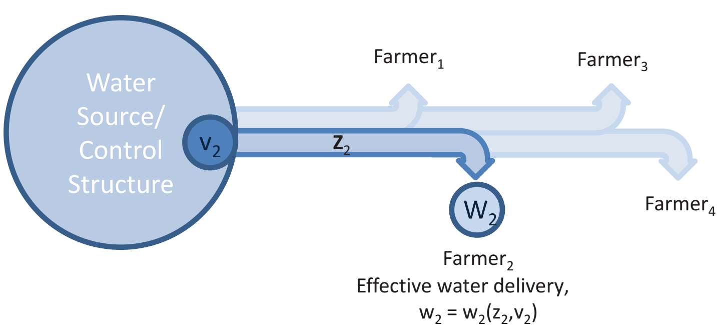

Figure 1. Conceptualizing surface-water delivery and loss.

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

where B_i is a single-valued globally concave net benefit function for consumer i; w_i is the effective water received by a consumer (which is a function of z_i, an exogenously set efficiency term that measures effective water transported to a given location, and v_i, which is actual surface water allocated to a given position); and $\bar{W}$ is the total surface-water endowment. B_i is twice differentiable ($B_i{}' \geq 0, B_i{}'' \leq 0$). For effective water transported, with greater delivery efficiency (i.e. z_i) or with more water allocated (i.e. v_i), effective water delivered increases. Since the canal command water allocation is entirely consumptive (usage and losses), we need not account for return flows (though it goes without saying that on-field application would result in flows to groundwater, and a more complete treatment would account for this); rather, what we do need to be concerned with are the efficiencies of the various canal segments, as affected by leakage to ground and evaporative losses. Let us call $z_i v_i$ the effective water delivered. First-order conditions result in the following efficiency condition:

$$\frac{\partial B_1(w_1)}{\partial w_1} z_1 = \frac{\partial B_2(w_2)}{\partial w_2} z_2 \tag{2}$$

This condition specifies that the marginal benefit of allocated water be equalized across farmers, with adjustments made for water delivery efficiency, a fairly standard result in allocation problems. (For a more detailed treatment of canal water allocative efficiency with losses, see Chakravorty & Roumasset, 1991.)

Having said this, a complete conceptualization of a water market for Pakistan would need to account for the very strong link between canal water and groundwater where the former recharges the latter. Groundwater recharge is a kind of "return" flow, and a complete model would incorporate groundwater usage and surface-based recharge. In fact, the best possible model would be dynamic, where groundwater is also allowed to act as intertemporal storage. Not including it in this model does not impact the thesis of this paper, as we are only dealing with the operation of the surface-water management system. A complete depiction would also include some of the more obvious economic frictions (such as matching buyers and sellers) associated with a market-driven canal water discharge pattern and the impacts it has on canal infrastructure; it would also include risk, by defining a "good" state (high discharge) and a "bad" state (low discharge) of the world. The fact is that there is variability in discharge, and farmers may place a value on reducing the variability of supply.

Pricing water, especially agricultural water, is a difficult undertaking, as it is difficult to measure the quantity of water used for irrigation (Stavins & Olmstead, 2006). Moreover, where there is a price, distortions in that price are common, often to support the production of staple crops or to accommodate the needs of well-connected and powerful elites (Rinaudo & Tahir, 2003). In other cases, water provision is unreliable. Farmers are often prepared to pay more for water (as is evidenced by their willingness to pay for more expensive groundwater), but only if they get access when they need it. Having said this, if even a close approximation to the correct price can be made, it will provide a way to approach efficient water use and will, moreover, provide water users with important price signals.

As Stavins and Olmstead state, injecting a strong price signal into the use and allocation of water can result in improvement in terms of allocative and conservation objectives. In all events, getting as close as possible to the true price for water will yield more socially efficient use outcomes. Water markets are a way to determine these true prices.

Current management of surface irrigation water in Pakistan

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 in water distribution at the distributary level. The second tier is farmer managed at the watercourse level (tertiary canals).

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), projects the provincial irrigation demand on a 10-day basis for the IRSA, which is responsible for making releases from the three major reservoirs (Tarbela, Mangla and Chashma) based on the projected demands (National Water Policy, 2004). Once the IRSA allocates water, the PIDA assumes responsibility for distributing that water internally within the canal commands under its jurisdiction. The 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 PIDA prices water, this price is not competitively set and 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 "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 each cycle a farmer has the right to use all of the water flowing in the watercourse (Bandaragoda, 1998). Bandaragoda's study (1998) found that this system is dynamic and subject to changes based on the needs of users and the supply of water. In practice, the *official* schedules have been superseded by *agreed-upon* schedules (i.e. schedules that users have informally agreed to, and that may deviate from the official *warabandi* schedule); these themselves are also subject to change, and result in the *actual* schedules. (The authors found that these modifications evolved due to the large temporal and spatial variation in canal-water availability.) And finally, these modifications are often shaped by pressure from influential farmers.

The farmers using the existing, relatively rigid irrigation system are dynamic and adaptive, and have introduced some flexibility to the system. Along with trading of irrigation turns, farmers also buy and sell turns. A significant portion of the water bought and sold at the tertiary level is canal water (not just groundwater). 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 both surface water and groundwater (see also Meinzen-Dick & Sullins, 1994). The bulk of water sales and purchases were groundwater, but a significant portion included surface water. Both surface-water and 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 involves unattractive transaction costs. (As an example, information frictions will enter as the distance between buyers and sellers increases, since buyers and sellers must be able to locate each other and the further apart they are the harder it will be for them to locate each other. Another example of increasing cost as the distance between buyer and seller increases is reduced conveyance efficiency.) Groundwater is, however, relatively easier to sell, since it is not bound by a schedule, as surface irrigation water is. Interestingly, they also found that farmers were willing to buy and sell partial canal turns.

There is a final issue of equity. Scholars who have studied the issue of equity of water distribution typically take an engineering perspective, where the object of study is the canal system, which needs spatial and temporal tweaking of rules and physical infrastructure to rectify inequities (see e.g. Bhutta & van der Velde, 1992; Latif & Sarwar, 1994; Anwar and Ul Haq, this issue). Typically, water engineers look at effectiveness and efficiency from the perspective of water volumes delivered. However, as in any system that caters to human demands, social elements form an important part of the canal system and influence the distribution of water. First of all, water user associations (*khal panchayat*) manage irrigation canals at the tertiary level, which implies that there is a distinct set of social costs and benefits to the way that the irrigation system is managed, operated and maintained. Moreover, as Rinaudo and Tahir (2003) noted, there is an entrenched rural agricultural elite that has traditionally benefited from privileged access to water. Finally, farmers do have to adapt to the deficit in canal water through groundwater pumping. Consequently, it is important to realize that along with the engineering issues that affect the irrigation system, there is a distinctly social layer of influence on the canal system's management that will require an economic analysis to gauge the equity and efficiency of water distribution among farmers along an irrigation canal.

The above briefly sets out the case for efficiency in surface irrigation water allocation and also describes the actual system of surface irrigation water allocation in Pakistan. Economically efficient allocation would see all farmers with equal marginal net benefits of irrigation water consumption. The current system of water management falls short from the perspective of allocative efficiency. The following sections describe the elements of a watercourse-level and a distributary-level water market, respectively.

Elements of a watercourse-level water market

Given the described context, is a market for irrigation water possible, given the existing physical environment? The following will show that a formal surface irrigation water market is possible at the watercourse and distributary scales; that is, that any watercourse in the IBIS can trade surface irrigation water with any other watercourse. Ideally, one would like to see a system that allows formal farmer-to-farmer trading. However, given the institutional boundary and the proportional or fixed outlet structures, a formal water market is easier to develop at the watercourse or distributary level. Given the extensive control infrastructure at the higher levels of the IBIS, adjusting discharge between canal commands and within canal commands (i.e. between distributaries) is possible. Within distributaries, control structures (outlets) are fixed (i.e. not adjustable without minor reconstruction), but have the potential for modification.

Moreover, since farmers already participate in informal water markets within watercourses, it may not be worth disrupting what seems to be working within watercourses. This is shown in Figure 2. Outlets connect directly to distributaries but can trade across higher tiers of the canal system. The "cloud" in the figure represents

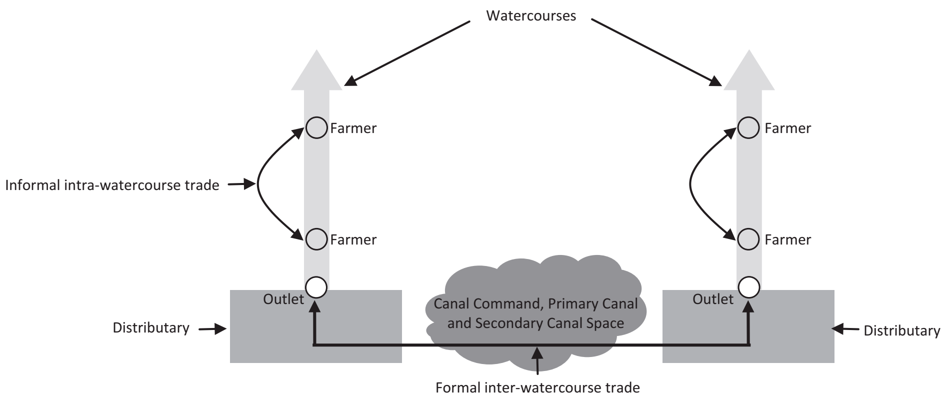

Figure 2. The formal water market is feasible at secondary-canal and higher levels of the canal system.

distributaries and higher levels of the canal system. The key is to determine what the scheme of modifications will be. The next few sections explore this.

To restate, the argument going forward is for water trading between outlet commands; that is, volumes must be traded between outlet commands (watercourses). Outlet-to-outlet trading of limited quantities preserves the *warabandi* schedule within the outlet command, which is needed because irrigation water resources are insufficient to irrigate all of the command area (see also Anwar and Ul Haq, this issue). Buying and selling relates to a portion of outlet discharge and a portion of a given growing season. It is assumed that farmers within a watercourse act in a united manner as they are collectively the sellers or buyers of water. Further, the outlet structure must be adjusted for a factor of the total water farmers within a watercourse are willing to sell or buy for the duration of the growing season designated for the trade by the parties involved. A growing season provides a logical stable period. Trading that is conducted over very short periods will increase the complexity of the sequence of outlet-hardware adjustment and the expense involved in trading. All outlets must of a uniform type (that is, proportional or non-proportional) within a distributary command, for ease in adjusting to net trades. The kind of buying and selling that is immediately possible is for the right to a portion of the discharge in a given watercourse to be allocated to another watercourse, with adjustment for transmission losses and, potentially, adjustment to watercourse intake for all other (non-trading) watercourses.

Before proceeding, it should be noted that the outlet hardware plays an important role in the type of trading that can happen. There are essentially two broad categories of outlet hardware (Novák & Nallur, 2007) in the IBIS. The first kind, called a proportional outlet, enables the discharge of a certain proportion of the discharge in the parent canal. Proportional outlets tend to vary their discharge with the variation in the parent channel's discharge. So, ideally speaking, a proportional outlet would produce 80% discharge in the outlet channel if its parent channel was producing 80% discharge. The second kind, called a modular outlet, produces a fixed (or almost fixed) discharge in the outlet channel, regardless of the discharge in the parent channel.

For a complete understanding and exposition, what we need to see is trading between two outlets (O_1, O_2) and the groups of outlets falling before them (G_1), between them (G_2), and after them (G_3). (See Figure 3.) G_i could contain zero, one or more outlets. The following discussion will assume lossless transfer, but the analysis applies equally if a loss

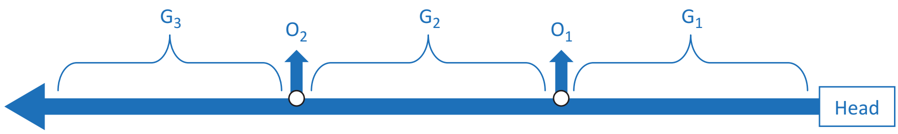

Figure 3. A representation of the canal system to demonstrate the feasibility of trade.

term is included, i.e. when conveyance efficiency is less than 100%, which is the case in the IBIS.

Non-proportional or modular outlets

A simple numerical example demonstrates the basic feasibility of trading within a canal between non-proportional outlets. Suppose daily flow into this channel is fixed at 50 units, where O_1 and O_2 take 10 units each and G_1, G_2 and G_3 take 10 units each. If O_2 sells half its discharge to O_1 (i.e. 5 units), O_1 ends up with 15, while O_2 is left with 5 (this is a downstream-to-upstream transfer). Then, without adjustment to G_1, G_2 or G_3 we simply adjust outlet O_1 to increase discharge to 15 units and adjust outlet O_2 to reduce discharge to 5 units over the growing season for which this agreement was reached. Since the outlets are non-proportional, G_1, G_2 and G_3 do not require any adjustment to their discharge, and the extra volume designated for O_1 simply passes by G_1 and enters O_1. G_2 captures its usual volume; O_2 captures a reduced volume; and G_3 captures its usual volume.

The other way around also works out quite simply. Again, suppose daily flow into this channel is fixed at 50 units, where O_1 and O_2 take 10 units each and G_1, G_2 and G_3 take 10 units each. If O_1 sells half its discharge to O_2 (i.e. 5 units), O_2 ends up with 15 units, while O_1 is left with 5 (this is an upstream-to-downstream transfer). Then, without adjustment to G_1, G_2 or $G_{3,}$ we simply adjust outlet O_2 to increase discharge to 15 units and adjust outlet O_1 to reduce discharge to 5 units over the growing season for which this agreement was reached. Since the outlets are non-proportional, G_1, G_2 and G_3 do not require any adjustment to their discharge, and the extra volume designated for O_2 simply passes by G_1 and enters O_1. G_2 and G3 capture their usual volume, while O_2 captures a reduced volume.

However, if canal flow varies, this system experiences problems. For non-proportional outlets, the sale is essentially of a particular volume. In the upstream-to-downstream transfer, if the discharge on some day reduces to 40 units, G_1 will take 10 units, O_1 will take 5 units, G_2 will take 10 units, and O_2 will take 15 units – leaving zero units for G_3.

Proportional or semi-modular outlets

Given that discharge varies on a daily basis in the IBIS, proportional outlets are preferable. We estimate that somewhere between 50% and 90% of all outlet structures in a given channel are proportional.

The key to making sure that trading works within a set of proportional outlets is that the proportions of all outlets between the trading outlets (inclusive of the trading outlets themselves) are adequately adjusted so that the effective proportion of discharge that an outlet takes does not change unless it is a trading outlet. Let us assume we want to start with all outlets and outlet groups capturing equal quantities of irrigation water. Then, G_1 takes 1/5 of all that passes by it; O_1 is set to take 1/4 of all that passes by it; G_2 is set to take $1/3$ of all that passes by it; O_2 is set to take $1/2$ of all that passes by it; and G_3 is set to take all of what passes by it (it is a terminal outlet group). To make this more concrete, suppose 50 units of discharge flow into the canal, which means that trading outlets (O_1 and O_2) and outlet groups (G_1, G_2 and G_3) get 10 units of discharge each (a fifth of 50 is 10, a quarter of 40 is 10, and so on; this will work for any initial discharge chosen).

Let us say that O_2 sells half its discharge to O_1; i.e. O_2 reduces its outlet so that its discharge is at half of the proportion it originally took, and correspondingly, O_2 expands its outlet so that its discharge is one-half more than the proportion it originally took. The adjustment of outlets actually has to be done carefully, and starting at the first outlet involved in the trade (whether it is buying or selling). If we do not propagate the adjustment properly, we run into trouble. Here is why. Let us naively increase O_1's fraction by one-half, to $1.5 \times 1/5 = 3/10$, and decrease O_2's fraction by one-half, to $0.5 \times 1/2 = 1/4$. G_1 takes $1/5$ of 50 units, which is 10 units (this is correct), but O_1 takes $3/10$ of 40 units, which is 12 units (incorrect); G_2 takes $1/3$ of 28 units, which is 9.33 units (incorrect); O_2 takes $1/4$ of 18.66 units, which is 4.67 units (incorrect); and G3 takes the remainder, 14 units (incorrect).

To propagate the changes in the system due to the trade correctly, all outlets must be adjusted. Here is how. G_1's intake fraction stays the same; O_1 (the first outlet involved in the trade) is adjusted to take $3/8$ (which gives it the correct discharge, 15 units); G_2's intake fraction is adjusted to $2/5$ (which gives it the correct discharge, 10 units); O_1's intake fraction is adjusted to $1/3$ (which gives it the correct discharge, 5 units); G_3 is not adjusted, and takes the residual. Thus, the adjustment of fractional intake is somewhat complicated in that a large group of outlets need to have their intake ratios revised.

Thus, all outlets in the channel must be adjusted, starting with the head-most outlet involved in the trade (in our case O_1) and including the tail-most trading outlet (in our case O_2) and all outlets in between (in our case, the outlet group G_2). We do not need to adjust the fractional intake for any of the outlets in G_1 and G_3. This is because the amount of water that effectively passes by either of those two outlet groups after trading between O_1 and O_2 is the same as before trading.[1]

What about the other way round, i.e. from upstream to downstream? In this case, here is how it would work. (Assume the same base case as before, i.e. 50 units of discharge and a half-of-discharge-at-outlet sale.) G_1's intake fraction stays the same; O_1 (the first outlet involved in the trade) is adjusted to take $1/8$ (which gives it the correct discharge, 5 units); G_2's intake fraction is adjusted to $2/7$ (which gives it the correct discharge, 10 units); O_1's intake fraction is adjusted to $3/5$ (which gives it the correct discharge, 15 units); G_3 is not adjusted, and takes the residual.

In the kind of trading described above, there are essentially three outlets that need adjustment: O_1, G_2 and O_2. Trading adjustments are fairly straightforward, as shown in Table 1 below (shaded rows mark structures that require no adjustment).

Thus, trading of irrigation water is feasible. Let us go through a complete adjustment cycle as an example. Consider the adjustment for an upstream-to-downstream trade, where O_1 trades a proportion d ($0 \leq d \leq 1$) to O_2. O_1's initial intake ratio is $\frac{a_{O_1}}{b_{O_1}}$ (reminding ourselves that a_{O_1} is the discharge captured by O_1, while b_{O_1} is the discharge that reaches structure O_1), and since it "sells" $a_{O_1}.d$ downstream, we subtract $a_{O_1}.d$ from a_{O_1} to get an adjusted ratio of $\frac{a_{O_1}-(a_{O_1}.d)}{b_{O_1}}$. Now a higher volume passes by G_2 (i.e. higher than the original b_{G_2}); therefore we adjust its intake ratio to $\frac{a_{G_2}}{b_{G_2}+(a_{O_1}.d)}$, adding what O_1 took out of its intake discharge to the discharge that reaches G_2 (the denominator term for G_2). Now

Table 1. Adjustments needed to structures for within-distributary trading.

Structure	Pre-adjustment intake ratio	Post-adjustment intake ratio: Upstream to downstream	Post-adjustment intake ratio: Downstream to upstream
G_1	$\frac{a_{G_1}}{b_{G_1}}$	$\frac{a_{G_1}}{b_{G_1}}$	$\frac{a_{G_1}}{b_{G_1}}$
O_1	$\frac{a_{O_1}}{b_{O_1}}$	$\frac{a_{O_1} - (a_{O_1} d)}{b_{O_1}}$	$\frac{a_{O_1} + (a_{O_2} d)}{b_{O_1}}$
G_2	$\frac{a_{G_2}}{b_{G_2}}$	$\frac{a_{G_2}}{b_{G_2} + (a_{O_1} d)}$	$\frac{a_{G_2}}{b_{G_2} - (a_{O_1} d)}$
O_2	$\frac{a_{O_2}}{b_{O_2}}$	$\frac{a_{O_2} + (a_{O_1} d)}{b_{O_2} + (a_{O_1} d)}$	$\frac{a_{O_2} - (a_{O_2} d)}{b_{O_2} - (a_{O_2} d)}$
G_3	$\frac{a_{G_3}}{b_{G_3}}$	$\frac{a_{G_3}}{b_{G_3}}$	$\frac{a_{G_3}}{b_{G_3}}$

the amount that reaches O_2 is higher; i.e. b_{O_2} becomes $b_{O_2} + (a_{O_1}.d)$, and since O_2 is also the recipient of the sale, its intake discharge is adjusted from a_{O_2} to $a_{O_2} + a_{O_1}.d$.

Adjusting outlets is well within the technical abilities of the agencies charged with maintaining the canal infrastructure.

Inter-distributary water trading

Figure 4 presents a schematic of inter-distributary trading. Inter-distributary trading requires adjustment of a few more structures or groups of structures; thus it presents us with a slightly different case from that discussed above.

But the assumptions from before must hold. How would the new ratios look in this situation? Before proceeding, some terminology to help understand the diagram and the ratio adjustments that follow. O_1 and O_2 are the two trading outlets, as before. The segment naming scheme is $G_{i.j}$, where i is the associated outlet number (thus, $i = 1$ for segments associated with O_1 and $i = 2$ for segments associated with O_2; while $i = D$ for segments associated with D_1 and D_2), and j is the segment number. D_1 signifies the structure that interfaces between the primary canal and the secondary canal (distributary) for O_1, while D_2 does the same for O_2. The results are shown in Table 2.

Outlet adjustment: cost and implications

At the trading-system level

There is clearly a distinct cost associated with a trading mechanism which requires the kind of adjustment that has been outlined above: that is the cost associated with modifying outlet structures (a transaction cost aside from the informational frictions involved in finding trading partners, environmental externalities and associated impacts on canal infrastructure of the modified discharge). This cost applies to the case of proportional outlets, since this type of outlet requires adjustment to propagate through the entire system. However, this cost falls as the numbers of outlets that require adjustment are overlapped by multiple

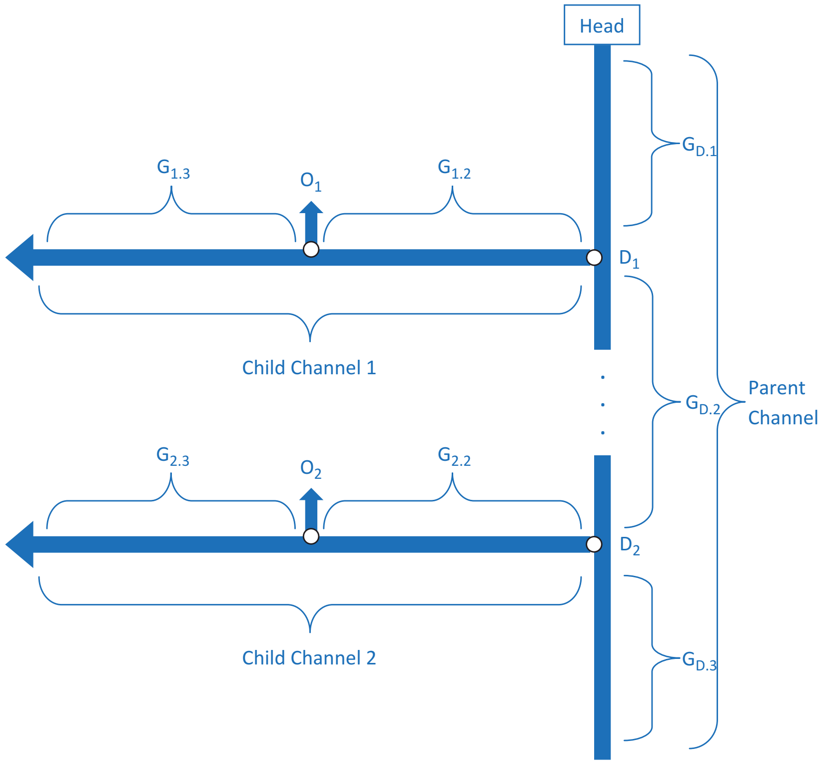

Figure 4. A representation of the canal system to demonstrate the feasibility of inter-distributary trade.

trading pairs. A trading pair is simply a pair of outlets that is in a water-trading relation (such as O_1 and O_2 from the previous discussion).

Two kinds of shared outlets need to be distinguished: outlets shared by a single trading pair; and outlets shared between multiple trading pairs, i.e. those that are part of more than one trading activity. Figure 5 illustrates this. As can be seen, the outlets that lie in Box **(a)** or Box **(b)** are exclusive to the trading pair (a)O_1—(a)O_2 or (b)O_1—(b)O_2, respectively. But the outlets in Box **(a)** + **(b)** are shared by both trading pairs; i.e. trading pairs (a) and (b) overlap those outlets. You can well imagine that this inter-trading overlap will increase as more outlets begin to trade canal water.

In fact, this overlap between trading pairs substantially decreases the transaction costs associated with outlet adjustment. Assume unit costs to adjust any given outlet. The trivial case is for a single trading pair with n outlets between them. In this case, the total cost of adjusting all outlets is n, and the cost per trading pair is also n (because $n / 1 = n$). For more complex cases, the key is figuring out the total cost of adjustment, and a simple algorithm helps calculate this. We define the concept of degree of overlap. This is simply a measure of how many trading pairs overlap on a given outlet. In the figure above, Boxes **(a)** and **(b)** mark segments with zero degrees of overlap, while Box **(a)** + **(b)** marks a segment that has one degree of overlap (since trading pairs (a) and (b) overlap on those outlets). Similarly, for a segment where k trading pairs overlap there are $k - 1$ degrees of overlap. Using this concept, we count all outlets by degree of overlap. (Think of it as buckets: the first bucket is for outlets that are not overlapped, the second bucket is for outlets that are overlapped

Table 2. Adjustments needed to structures for across-distributary trading.

Structure	Pre-adjustment intake ratio	Post-adjustment intake ratio: Upstream to downstream	Post-adjustment intake ratio: Downstream to upstream
$G_{D.1}$	$\frac{a_{G_{D1}}}{b_{G_{D1}}}$	$\frac{a_{G_{D1}}}{b_{G_{D1}}}$	$\frac{a_{G_{D1}}}{b_{G_{D1}}}$
D_1	$\frac{a_{D_1}}{b_{D_1}}$	$\frac{a_{D_1} - (a_{D_1} d)}{b_{D_1}}$	$\frac{a_{D_1} + (a_{D_2} d)}{b_{D_1}}$
$G_{1.2}$	$\frac{a_{G_{12}}}{b_{G_{12}}}$	$\frac{a_{G_{12}}}{a_{D_1} - (a_{D_1} d)}$	$\frac{a_{G_{12}}}{a_{D_1} + (a_{D_2} d)}$
O_1	$\frac{a_{O_1}}{b_{O_1}}$	$\frac{a_{O_1} - (a_{O_1} d)}{(a_{D_1} - (a_{D_1} d)) - a_{G_{12}}}$	$\frac{a_{O_1} + (a_{O_2} d)}{(a_{D_1} + (a_{D_2} d)) - a_{G_{12}}}$
$G_{1.3}$	$\frac{a_{G_{13}}}{b_{G_{13}}}$	$\frac{a_{G_{13}}}{b_{G_{13}}}$	$\frac{a_{G_{13}}}{b_{G_{13}}}$
$G_{D.2}$	$\frac{a_{G_{D2}}}{b_{G_{D2}}}$	$\frac{a_{G_{D2}}}{b_{G_{D2}} - (a_{D_1} - (a_{D_1} d))}$	$\frac{a_{G_{D2}}}{b_{G_{D2}} - (a_{D_1} + (a_{D_2} d))}$
D_2	$\frac{a_{D_2}}{b_{D_2}}$	$\frac{a_{D_2} + (a_{D_1} d)}{b_{D_2} - a_{G_{D2}}}$	$\frac{a_{D_2} - (a_{D_2} d)}{b_{D_2} - a_{G_{D2}}}$
$G_{2.2}$	$\frac{a_{G_{22}}}{b_{G_{22}}}$	$\frac{a_{G_{22}}}{a_{D_2} + (a_{D_1} d)}$	$\frac{a_{G_{22}}}{b_{D_2} - a_{G_{D2}}}$
O_2	$\frac{a_{O_2}}{b_{O_2}}$	$\frac{a_{O_2} + (a_{O_1} d)}{(a_{D_2} + (a_{D_1} d)) - a_{G_{22}}}$	$\frac{a_{O_2} - (a_{O_2} d)}{(b_{D_2} - a_{G_{D2}}) - a_{G_{22}}}$
$G_{2.3}$	$\frac{a_{G_{23}}}{b_{G_{23}}}$	$\frac{a_{G_{23}}}{b_{G_{23}}}$	$\frac{a_{G_{23}}}{b_{G_{23}}}$
$G_{D.3}$	$\frac{a_{G_{D3}}}{b_{G_{D3}}}$	$\frac{a_{G_{D3}}}{b_{G_{D3}}}$	$\frac{a_{G_{D3}}}{b_{G_{D3}}}$

once, and so on.) This will provide a total count for outlets that need adjustment and, since we assumed a unit cost, the total cost as well. In terms of notation, n refers to the number of outlets between a trading pair, n_0 to the outlets that have zero degrees of overlap, n_1 for outlets that have one degree of overlap, and so on. For simplicity, assume that all trading pairs have the same number of outlets between them, i.e. n.

To illustrate, suppose there are two trading pairs (as in Figure 5), with n outlets between the pairs. If there is no overlap in outlets between the two trading pairs (i.e. there is no (a) + (b) segment as indicated in the figure above), then the total cost of adjustment is $2n$ and the cost per trading pair is n. But if there is overlap, say n_1 outlets overlap (for $0 \leq n_1 \leq n$), then the total cost is the sum of the outlets that have zero degrees of overlap (i.e. n_0 for each trading pair) and those that have one degree of overlap (i.e. n_1), or $n_0 + n_1$. This implies an average outlet adjustment cost of $(n_0 + n_1)/2$. We can generalize this for k trading pairs to:

$$\frac{\sum_{i=0}^{k-1} \{n_i\}}{k}$$

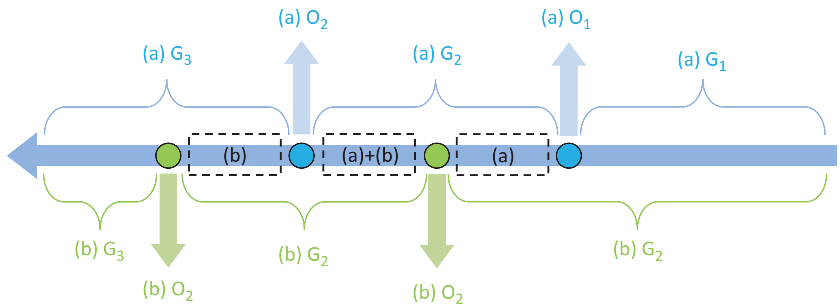

Figure 5. Overlapping outlet trading pairs.

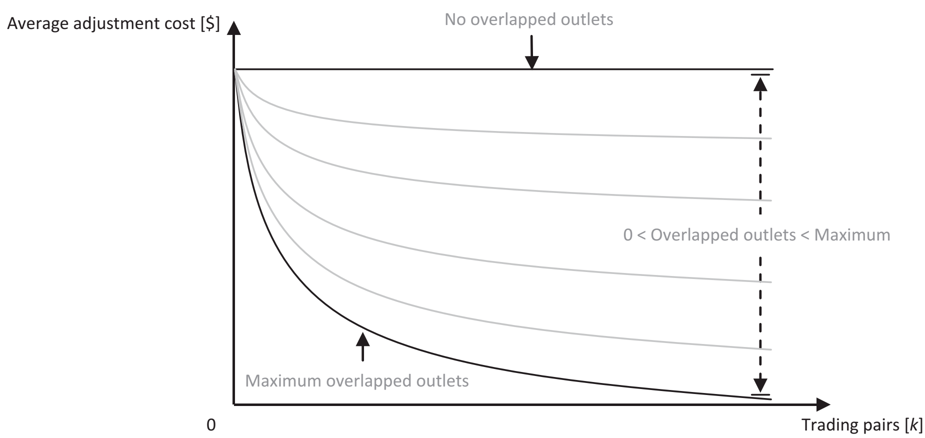

Figure 6. Falling average outlet-adjustment cost.

Now this set-up can be used to demonstrate that average adjustment costs per trading pair decline with greater overlap and a larger number of trading pairs. Let us take two extreme cases: the case of no overlap $\left(\text{i.e. } \sum_{i=0}^{k-1}\{n_i\} = kn\right)$ and the case of maximum overlap $\left(\text{i.e. } \sum_{i=0}^{k-1}\{n_i\} = n\right)$. Then, for $k = 1, 2, \ldots, m$, we see that average adjustment costs stay constant for the zero overlap case – i.e. $\frac{n}{1}, \frac{2n}{2}, \ldots, \frac{mn}{m}$ – and reduce to a declining exponential function for the maximum overlap case: $\frac{n}{1}, \frac{n}{2}, \ldots, \frac{n}{m}$. This is true for any degree of overlap (not just the maximum, n), but the extreme cases help us see that with greater overlap and more trading pairs, the average adjustment cost falls non-linearly (Figure 6 shows this).

At the trading-outlet level

The flip side of the outlet-adjustment cost is the impact it has on the trading watercourses. With the use of a simple model of the outlet command's optimization problem, we can demonstrate that as the number of overlapping trading pairs increases, watercourses are more willing to engage in trade. Mathematically, it is a profit-maximization problem:

$$\max_{m} \left\{ \Pi\,(w) = Y\,(w)\;P^{Y} - c - f\,(m)\;P^{f} - m\,P^{w} \right\}$$
$$\text{subject to}$$
$$w = V + m,$$
$$0 \leq V, 0 \leq m, 0 \leq w, \tag{3}$$

where $Y\,(w)$ is a single-valued globally concave yield function in w, P^{Y} is the price of output, c represents non-water costs for the outlet, $f\,(m)$ defines the number of outlets modified for a given quantity of water (i.e. if the outlet in question engaged in trade, what would be the number of outlets needing modification; presumably, if more water is sought, more outlets will be modified), P^{f} is the marginal cost of outlet modification, m is the quantity of water bought (or sold) in trade, P^{w} is the market price of water, and V is the historically based endowment of water for the outlet. Essentially, outlets must choose the amount of water they buy or sell. Substituting in constraints and assuming an interior solution, first-order conditions are

$$\frac{\partial Y}{\partial m} P^{Y} = P^{w} + \frac{\partial f}{\partial m} P^{f} \tag{4}$$

At the efficient quantity of water traded, outlets equate the marginal value product of output to the marginal benefit of a unit of water (the price of water) and the marginal value product of outlet adjustment. If the marginal cost of outlet adjustment (P^{f}) is a decreasing function of the number of overlapping trading pairs (as discussed in the previous section), then a small number of overlapping trading pairs results in high cost of adjustment. If the marginal cost of outlet adjustment increases (i.e. P^{f} increases), outlets will reduce their demand for traded water (m).

It is far more enlightening to "see" this effect in the case of a water-buying outlet. Refer to Figure 7. The figure shows a trading outlet in deficit with an allocated volume of V. With a high marginal cost of outlet adjustment (P'^{f}), the optimal traded-in quantity of water is m' – for the given market price of water (P^{w}) and the revenue function ($Y(w)P^{y}$), profits

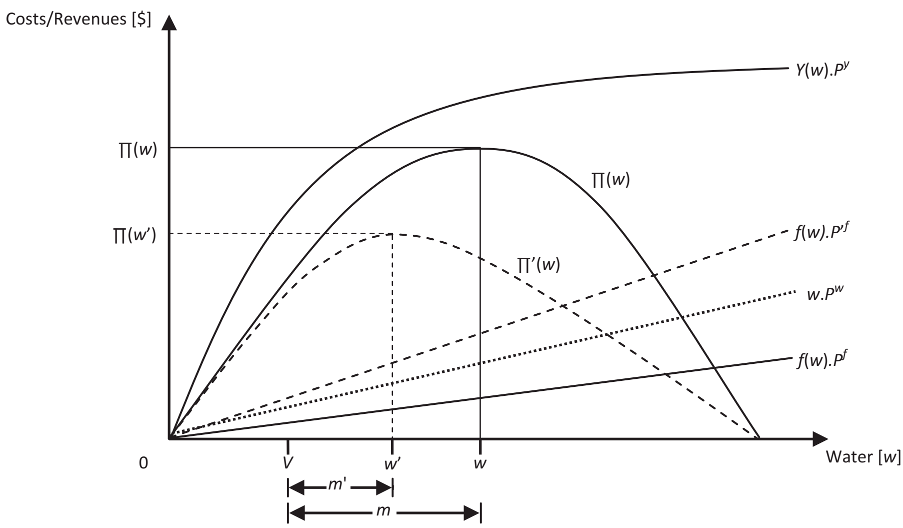

Figure 7. Outlets reducing the amount of traded water they use as the marginal cost of outlet adjustments increases.

are $\Pi'(w)$. With a lower marginal cost of outlet adjustment (P^f), the outlet command is willing to buy more water ($m > m'$) because the profit function actually shifts to a higher level, $\Pi(w)$. A similar analysis can be shown for a water-selling outlet, except that a higher price for outlet adjustment will reduce the outlet's willingness to trade. (Note that for a water-selling outlet, V is higher than what is "needed" – thus the desire to sell excess water.)

Implications

Physical implications

First and foremost, farmers own the historic proportion of parent-channel discharge that makes it to their outlet. Therefore, reallocation of water is not unjust, i.e. no water is being taken away from farmers, and they start at a historically true baseline. Farmers are owners of their fraction of water and are free to sell it to someone upstream or downstream. This is important, as it forms the very basis of a system of trading.

Next, the head of the system needs to be defined before any trading takes place. This will define the valid area within which trading can take place and is also needed for correct calculation of the conveyance efficiency.

In non-proportional-outlet trading, the quantity demanded must meet the minimum constraint of being greater than the loss; that is, the quantity demanded by any farmer must exceed total conveyance losses up to the point of purchase. For proportional-outlet trading, conveyance efficiency acts as an overall constraint to trading, in that the discharge in a given channel should not fall outside its optimal operating window. This is an issue for inter-distributary trading, where transactions across distributaries may push the total discharge in a distributary outside the normal operating range. If inter-distributary trade changes discharge flows significantly, canals might cease to operate effectively, the *wara-bandi* system might be affected, and sedimentation rates might increase. However, canals do have a cleaning schedule and an associated cleaning cost. As with any infrastructure, this is a maintenance cost and something that occurs already. If there is added silt build-up, the frequency of cleaning can be increased and added to the transaction cost. This may or may not push certain transactions out of the envelope of financial feasibility.

As was demonstrated above, both upstream-to-downstream and downstream-to-upstream trades can take place. This has a corollary: downstream-to-upstream sales will tend to get "weighted up" in terms of the proportion bought and sold, since the total loss is reduced (a consequence of the smaller distance that water must travel from the canal head to a recipient), while upstream-to-downstream trades will tend to get "weighted down" in terms of the proportion bought and sold, as water losses accumulate over the distance travelled in the channel network.

Finally, trading of water will impact local groundwater quality and access. The current allocation means that groundwater is recharged and extracted in a particular manner which farmers are accustomed to (even if the scenario is dynamic, such as a steadily falling water table). Trading will reorganize this pattern of recharge and extraction. This paper does not speak to optimal allocation with groundwater as a constraint – only to the adjustment and feasibility of the existing system – but any market would need to account for groundwater impacts.

Institutional implications

Government departments would have to be willing to modify outlet structures and adjust distributary gates to ensure that they correctly reflect season-level trades. Moreover, the government would have to provide reliable predictions of distributary flows based on seasonal forecasting, so that agents at the distributary or watercourse level can decide whether and how they want to engage in trading. A recently updated, 10-day time-step Indus Basin Model managed at the Water and Power Development Authority for the IRSA can help provide such information (see also Yang et al., this issue, on a monthly version of this model).

At present, the government does receive a small sum of money from farmers (called an *abiana* or water tax); it is not nearly enough to cover maintenance expenses. With a system that trades, the government could tax trades, or continue to charge the *abiana*, or both. For watercourses, this task would be taken up by water user associations (*khal panchayat* to *khal panchayat*) across the water course. The 1997 PIDA reform should generally support water trading, given its focus on decentralization of irrigation water management.

As an additional point to the above, the total cost of outlet adjustment must be lower than the overall transaction value (that is, the total net benefits from trading must be positive and higher than without trading, taking into account outlet-adjustment expenses). That applies to all transactions in the canal system where this trading takes place. In the framework set up above for trade in a setting with proportional outlets, the set of outlets spanning the two trading outlets (O_1 and O_2) and all those in between (G_2) had to be modified. At first glance it would seem that the greater the number of outlets in G_2, the greater the overall cost of a transaction. But the fact is that as the number of trading outlets increases and the number of overlapping outlets increases, the cost of adjusting outlets decreases (as demonstrated in the previous section).

For trading between watercourses, farmers within a watercourse must coordinate to produce a total excess demand or supply number for their watercourse, and watercourse presidents must coordinate to determine selling and buying. Institutionally, *khal panchayat* presidents already meet at the distributary level (a consequence of existing reform). Furthermore, outlet-to-outlet trading allows for organic development of trading institutions from the bottom up. Outlets in a neighbourhood of the distributary can begin trading and slowly expand to farther reaches of the distributary system.

Importantly, the trading described above does not disturb the existing *warabandi* system at either the distributary or watercourse levels. The need of operation as a private water market requires a host of third-party service providers. Banks must be employed to formalize and guarantee trades and ensure that payments are timely and trusted. Middle-men or traders are needed to help arrange trades, matching buyers and sellers. This could also be implemented in cross-distributary farmer organization or cross-watercourse *khal panchayat* meetings. Finally, a technical institution that is trusted by all to keep track of the feasibility and overall adjustments to be made to inlet structures will be needed.

Conclusions

This paper argues that a water market is physically feasible at both the watercourse and distributary levels. Watercourses can buy and sell water as long as it is a fraction of their discharge over the course of a season.

The trading system described here is an enhancement and modification of the ongoing decentralization of the irrigation system called "irrigation management transfer" (IMT), a recent, large-scale policy implemented by the government (Hassan, 2009). The World Bank proposed IMT in 1994 based on similar management-transfer experiences in other countries. Instead of a market on which to trade water, the underlying idea behind this policy was to decentralize the system by handing over management, operation and maintenance of secondary canals to FOs. FOs were to be placed under the authority of area water boards (AWB), which report to the Provincial Irrigation and Drainage Authority.

For the most part, AWBs correspond to canal commands, though sometimes more than one canal command can fall under the authority of an AWB. Each canal command has multiple FOs in charge of the secondary canals within the canal command. In fiscal year 2006–07, according to the Punjab government, 100 FOs were formed in 5 canal commands (Institutional Reforms in Irrigation Sector Punjab Province & Progress & Achievements, 2007). Eventually, the PIDA hopes to hand over all secondary canals to FOs (under their respective AWBs) through IMT.

The government is pushing through reform that will decentralize the system by requiring the installation of institutions at multiple physical levels of the system (i.e. at the outlet command, distributary command and canal command levels). The water trading described in this paper can quite easily be added on to the IMT structure as it exists today. However, it is important that any market-type trading is done using real private players (banks, traders and technical bodies) and that the IMT institutions that are being installed assist with water trading.

While this study has focused on surface-water trading, future research will assess the implications for externalities through changing groundwater availability. This is challenging, as groundwater is a more complex (and invisible) common-pool resource with complex management requirements (Provencher & Burt, 1993).

Note

1. In our numeric example, 50 units passed by G_1 and 10 units by G_3 both before trading and after, implying that no adjustment was needed. This will hold for any quantity of water flowing by. Adjustments to outlet discharge need only be done in the canal reach that is actually trading, i.e. the two trading outlets and all outlets between them.

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