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Research Report

Farmer Response to Rationed and Uncertain Irrigation Supplies

C. J. Perry
and
S. G. Narayanamurthy

International Water Management Institute

Research Reports

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Summary

Agricultural production, even in irrigated areas, is increasingly water-constrained. The shortage may be seasonal, year-round, or progressive as demands from additional agricultural use or from other sectors increase. Managing shortage is therefore a critical issue in irrigation. This situation is further complicated by uncertainty. Even where water supplies are derived from storage reservoirs, unforeseeable events often disrupt original service targets—rainfall causes a sudden decline in demand, followed by very high requirements as many areas simultaneously dry up; unscheduled demands to "priority" uses (power, municipal, and industrial) result in reduced availability for irrigation; temporary technical failures disrupt scheduled supplies, with further effects on future demands, and so on.

The report explores the theoretical and actual responses of farmers faced with irrigation supplies that are limited in relation to available land and labor resources, and where the actual schedule and available volume for delivery are uncertain. It is shown that water scarcity should induce farmers to underirrigate some crops in relation to full potential evapotranspirative demand, because reductions in yield may be proportionally less than reductions in water applied. This strategy increases returns to water.

However, where water availability (and hence evapotranspiration) fall below a certain point, the value of the crop can fall to zero—either because the crop actually dies, or because the product (grain, cotton, or whatever) is of such low quality as to be unmarketable. This possibility implies that a strategy of deficit irrigation, when irrigation supplies are uncertain, increases the risk of financial loss. There is thus a theoretical tradeoff between under-irrigation and uncertainty.

Based on field data from northwest India, where irrigation systems were designed and are still operated to ration scarce water among users, the theoretical model is confirmed, showing that even in very large systems it is possible to encourage individual farmers to maximize returns to water. It is further confirmed that the extent to which they pursue this strategy is affected by the reliability of the service they receive.

Farmer Response to Rationed and Uncertain Irrigation Supplies

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Introduction

Managing irrigation systems for maximum productivity under conditions of shortage and uncertainty is a critically important challenge to irrigated agriculture.

Constraints to the availability of water for irrigated agriculture are increasingly evident in many countries. Shortage may be seasonal, year-round, or progressively significant as demands from other users expand. Within the agriculture sector, increased demand results from intensified cropping or a switch to more water-intensive crops, and from diversion of supplies to newly constructed systems. Expanding nonagricultural requirements include domestic and industrial demands (in which pollution of water is often as significant as physical consumption), in-stream uses such as navigation, and, increasingly frequently, for environmental purposes.

Scarcity is further complicated when water supplies are uncertain. The effects of anticipated shortages can be managed in such a way as to minimize negative impacts—by scheduling breaks in service at times of low or noncritical demand, or reducing the area planted in a particular season. Uncertainty—not knowing what the overall supply will be, or when shortages will occur—precludes such management.

Even where water supplies are derived from storage reservoirs and thus are known for the season—unforeseeable events often disrupt original service targets. Rainfall may cause a sudden decline in demand, followed by very high requirements as large areas of crop simultaneously dry out; unscheduled allocations to “priority” uses (power, municipal, and industrial) result in reduced availability for irrigation; temporary technical failures disrupt scheduled supplies, with further effects on future demands, and so on.

Expanding supply through construction of new storage works simultaneously increases both the quantity of water available, and reduces uncertainty by allowing retention of surplus flows for use during periods of deficit—at a minimum, for short intraseasonal shortages, and at the other extreme, for multiyear carryover during persistent droughts.

We first discuss farmer response to scarcity under various scenarios of water distribution within an irrigation system. Second, we examine the theoretical responses of an individual farmer when faced with shortage or uncertainty, and hypothesize that the responses are distinct and conflicting.

We then examine field data to test these hypotheses, and demonstrate that even very large irrigation systems, serving many hundreds of thousands of individual farmers, can be operated so as to induce a socially efficient response at the farm level to shortage and uncertainty, so that farmers’ behavior is consistent with that which maximizes the benefit to society.

Definitions

By the term "scarce," we mean that water availability is the primary constraint to production, while land and labor are underutilized. Any increase in the availability of water would lead to higher utilization of land available to the farmer, and increased use of other inputs—increasing the area irrigated, and using more labor, fertilizer, and other inputs on this extra land.

By the term "uncertain," we mean that the amount and timing of water that will be received are not known—rainfall may be more or less than average; and actual deliveries may differ from plans as a result of unforeseeable events (river inflows differing from expectation, a rainstorm disrupting schedules, a canal breach, unexpected demands from other uses, theft by upstream users, etc.).

Unless otherwise stated, the term "yield" has its traditional meaning of crop production per unit of land.

Allocation of Water within a Project

Farmers seek to maximize the returns to the resources applied to their activities. In particular, they try to maximize returns to those resources that are scarce. In certain areas of Africa, where land is plentiful, farmers seek to maximize returns to labor (Sanders 1997), the constraining resource. In Asia, labor is generally more plentiful, and either land or water is more often the constraining resource. Where land is constrained, yield per hectare, the most commonly used indicator of agricultural productivity, will also correlate closely with the farmers' objective of maximizing net returns to land. But where water is constrained, returns to water consititute an appropriate objective for a project (or society) as a whole. How limited quantities of water are allocated among farmers will strongly affect their individual responses, and the appropriateness in the aggregate of that response from society's perspective.

One way to allocate shortage is to allow (by design, or more commonly, by default) those favored by location or influence to take what they want, while others receive the erratic, residual supplies.

In this scenario, those farmers enjoying unrestricted access would irrigate their entire landholding, and behave as if land is the constraining resource, choosing crops that have high returns to land, while perhaps consuming a large amount of water (sugarcane, for example).

Alternatively, when the cropping pattern is controlled to eliminate or reduce crops that give low returns to water, but the authorized cropping pattern can be fully irrigated, farmers will try to maximize returns to the land that they are allowed to irrigate satisfying the full irrigation requirements of the crop, and be relatively unconcerned to try to exploit residual soil moisture or rainfall because this will require extra effort and possible risk, if anticipated supplies do not materialize. Further, the agency operating the scheme, in authorizing a specific cropping pattern, will tend to be conservative so as to minimize the difficulties of management, and the possibility of failure.

In a third scenario, when the available water is rationed uniformly per unit of land

and cropping patterns are left to the farmers' discretion, all farmers face shortage and consequently all are likely to pursue strategies that result in high returns to water. In the absence of externalities, society will tend to benefit from this third approach, which encourages the maximum returns to the limiting resource. Such an approach involves either selection of crops that have high returns to water, or deliberately under-irrigating the planted crops. The latter approach—deficit irrigation—has been widely studied and reported (Butter 1996; Downey 1972; English and Raja 1996; English, Musick, and Murty 1990; Hall and Buras 1961; Shaozhong and Minggang 1992).

Clearly, pursuing a strategy of extreme deficit irrigation (by grossly oversizing irrigation commands in relation to anticipated water availability) will not be economically viable. Once returns to water have reached their maximum level, benefits remain fixed (and indeed eventually fall as water supplies per unit land become impracticably small) while construction, operation, and maintenance costs rise with increased command area. However, providing the possibility of "stretching" irrigation water to ingenious farmers pursuing maximum returns to the scarce resource, appears to be an option worth considering.

The Theoretical Relationship between Water Applied, Water Consumed (ET), and Yield

Various researchers (Hanks, Gardner, and Florian 1969; Downey 1972; Stewart and Hagan 1973) have investigated the relationship between ET and yield. FAO Irrigation and Drainage Paper No. 33 (FAO 1979—hereafter referred to as FAO 33) is probably the most complete summary of available data, and is the basis for the following discussion.

Many crops exhibit strongly different sensitivities to soil moisture stress at different stages of crop growth; stress results in actual evapotranspiration (ETa) being less than that required for full potential yield from the crop. When stress occurs at a particular stage, the relationship between ETa and yield is linear. The following form depicts the relationship (FAO 33):

$$Y = (1 - k_y) + k_y \cdot ET_a/ET_m \qquad (1)$$

where,

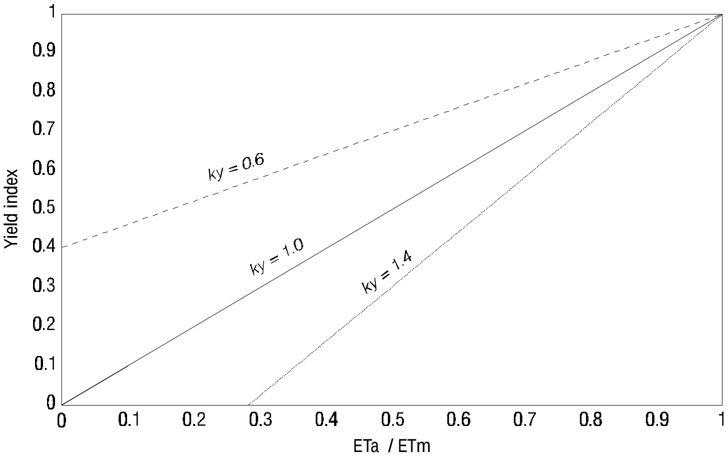
Y = Relative yield (potential yield being unity)

ET_m = the full evapotranspiration requirement of the crop during its growth period to reach potential yield

ET_a = Actual evapotranspiration by the crop

k_y = Yield coefficient

FIGURE 1.
Yield versus ET_a for various values of k_y.



It can be seen in figure 1, if k_y is equal to unity, yield will be directly proportional to ET_a. If k_y is positive, but less than unity, yield falls proportionately more slowly than ET_a (that is, yield is relatively insensitive to irrigation deficits), and if k_y is greater than unity, then yield is disproportionately sensitive to irrigation deficits.

In fact, for many crops k_y varies sharply during the growing season. For example, in the case of wheat, k_y ranges from less than 0.5 during the stage of vegetative growth to about 3.0 during the flowering stage (FAO 33). This leads to the possibility of selective reduction in water deliveries at less-critical growth stages, while retaining full deliveries at the critical stages, resulting, effectively, in a convex relationship between ET_a and yield. Where shortages are minor, they are absorbed during periods of low-yield sensitivity. More severe shortages require reductions in water supplied during progressively more sensitive periods leading to a piecewise linear response to shortage, with yield falling more sharply for higher degrees of shortage. Other researchers (below) have formulated similar response functions, which for the purposes of this analysis are easier to manipulate. But the conclusions presented can be demonstrated to hold for any relationship between water and yield that is progressively more sensitive as water shortage increases.

The Relationship between Water Applied and ET

Vaux and Pruitt (1983) set out the case that while the relationship between crop transpiration and crop yield is essentially linear, the relationship between yield and water applied is nonlinear because evaporation and other losses increase disproportionately at higher levels of water application.

Earlier, Hargreaves (1977) presented a similar conclusion, on the basis of extensive analyses of field data for a wide range of forage and grain crops, with the following relationship between moisture availability and yield:

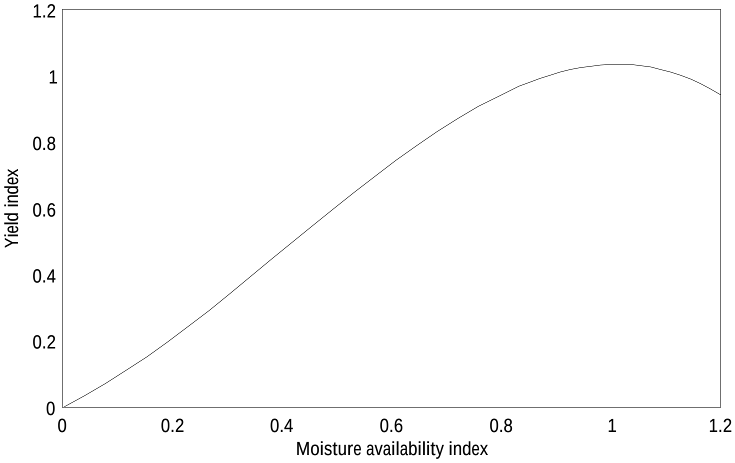
$$Y = 0.8 \cdot X + 1.3 \cdot X^2 - 1.1 \cdot X^3 \qquad (2)$$

where,

Y = Relative yield (potential yield being unity)

X = Moisture availability (quantity required for full potential evapotranspiration for all growth stages being unity)

FIGURE 2.
Hargreaves' relationship between moisture availability and yield.



The resulting relationship between water availability and yield is shown in figure 2. This relationship is based on field observations for a wide range of field and forage crops, and is of relevance to the data presented later. Its formulation is particularly suitable for the analysis proposed here as it can readily be manipulated to produce a continuous function of gross or net returns to land and water. In fact, any convex function would yield the same conclusions as are later derived from Hargreaves' formula.

For water availability in the range 30–70 percent of the requirements for full yield, the yield-availability relationship is essentially linear (as proposed by Vaux and Pruitt); above 70 percent water availability, the yield response declines pronouncedly.[1]

However, this formulation is not adequate to predict farmer response to water scarcity. First, it is formulated in terms of returns to land (for which yield is a direct proxy), while water-short farmers are interested in returns to water; second, yield is a proxy for gross returns, and fails to account for input costs—farmers are interested in net profit, not gross income; and third, it fails to incorporate the impact of additional (nonirrigation) sources of water—rainfall, residual moisture, and capillary rise. These revised objectives are incorporated into Hargreaves' formula in the following steps.

First, net value added per unit area may be calculated as:

$NVP_a = (P \cdot \text{Yield}) - (\text{Yield} \cdot C_v) - C_f$

Or $NVP_a = (P - C_v) \cdot \text{Yield} - C_f$ (3)

where, NVP_a = Net value of production per unit area

P = Unit value of output

C_f = Fixed costs per unit area (e.g. ploughing, seeds, and rent)

C_v = Variable costs per unit yield (harvesting, fertiliser)

Second, to introduce the possibility of nonirrigation sources of water, we modify Hargreaves' formula (2), replacing moisture availability (X) with its two components parts—irrigation and other sources:

$Y = 0.8 \cdot (I+R) + 1.3 \cdot (I+R)^2 - 1.1 \cdot (I+R)^3$ (4)

where, I = Irrigation supply per unit area

R = Nonirrigation water available to the plant (rainfall, residual moisture, and capillary rise)

Substituting in (3)

$NVP_a = (P - C_v) \cdot [0.8 \cdot (I+R) + 1.3 \cdot (I+R)^2 - 1.1 \cdot (I+R)^3] - C_f$ (5)

[1] It is worth noting (as this point has caused confusion to many with whom these ideas have been discussed) that the linear relationship between yield and ET (or water availability) is not the same as a proportional relationship. A proportional relationship requires both linearity and interception of the linear extension with the origin. The second criterion is not met here.

Distinguishing between I and R is critical to the analysis. If the quantity of irrigation water available (I) is fixed, the depth of water applied will be inversely proportional to the area irrigated.[2] Hargreaves' formula shows that spreading the irrigation supply will give progressively lower yields (per unit land) over progressively larger areas, and the tradeoff between the fall in yield per unit land and the increase in land maps out the trend in the productivity of water. We are, however, at this stage only tracing the productivity of the (fixed) irrigation supply (I). The nonirrigation supply (R), is quite different. As we increase the irrigated area, we progressively "capture" the productivity of the water available (from rain, soil moisture, or capillary rise) from the incremental land, giving an additional return to the irrigation water. If the nonirrigation water is insufficient for rain-fed cropping, this incremental productivity comes at no opportunity cost, as the moisture would otherwise simply evaporate. If rain-fed cropping is possible, then the return to irrigation water should be calculated net of the value of rain-fed production.

Here, we assume that rain-fed production is not feasible, so that the total value of production is given by multiplying NVP_a by area irrigated. If we assume the quantity of irrigation water available (I) is the amount required to give full potential yield on one unit of land, then the quantity applied to the area actually irrigated is equal to I/Area, giving:

$$NVP_t = \text{Area} \cdot \{(P - C_v) \cdot [0.8 \cdot (I/\text{Area} + R) + 1.3 \cdot (I/\text{Area} + R)^2 - 1.1 \cdot (I/\text{Area} + R)^3] - C_f\} \qquad (6)$$

where,

NVP_t = Total net value of production ($NVP_a \cdot$ Area)

We impose one further relationship, namely that below some critical level of yield, the value of the output is zero. The rationale for this is that output *quality* varies with yield. At very low levels of yield, grains are shriveled and unusable. The value at which this limitation is applied is arbitrary, but Hargreaves notes that few observations of yield below 35 percent potential yield are available. We therefore take this value as that, below which, "useful" yield is deemed to fall to zero.

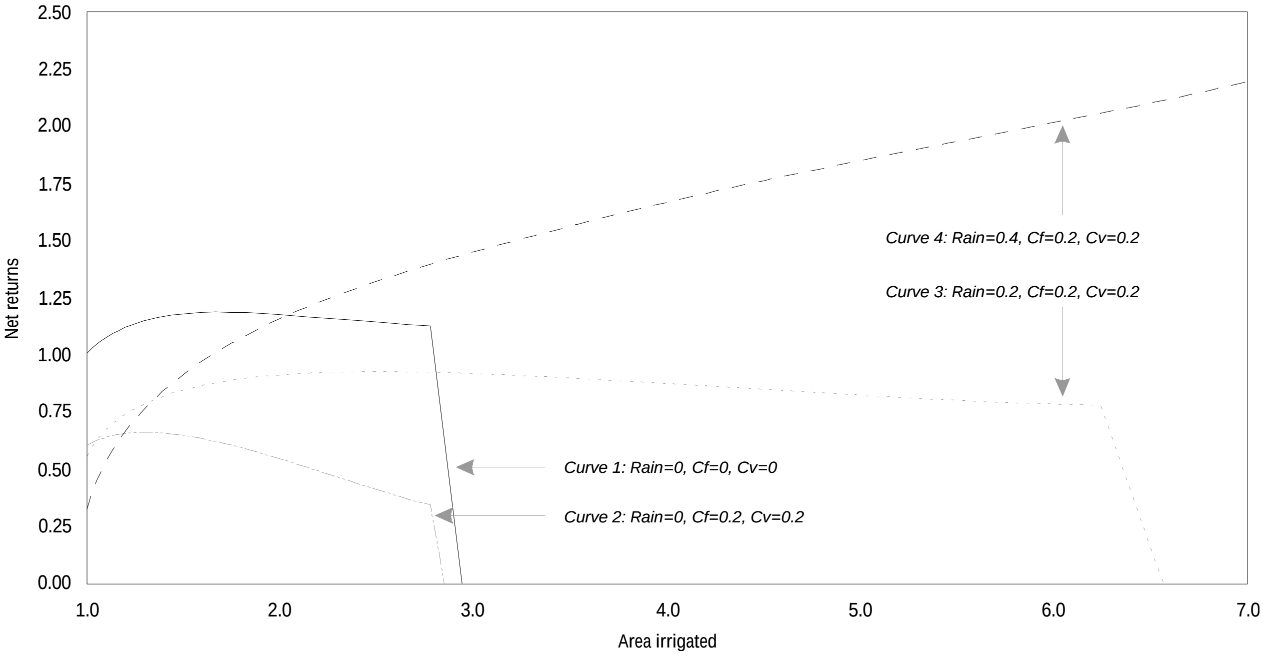
Figure 3 shows a number of possible relationships between net value of production and water availability based on equation 6 above.

Curve 1 is the situation where costs are zero, and only irrigation water is available. It corresponds to Hargreaves' basic formula, but is translated into returns to water. Optimum area irrigated is close to double that for maximum returns to land, while the net value of production (which, with costs at zero is identical to gross value) is about 20 percent higher than at maximum yield per hectare, where the area irrigated is unity.

Curve 2 introduces fixed (area dependent, C_f) and variable (yield dependent, C_v) costs at a level of 20 percent of gross production value. The effect of this is (obviously) to reduce the net value of production and to shift the optimum area irrigated sharply back towards the area corresponding to maximum yield per hectare.

[2] If we have 5,000 m^3 available, and apply this to 1 ha, we have an irrigation depth of 500 mm. If we choose to irrigate 2 ha, the irrigation depth applied will be 500/2, or 250 mm.

FIGURE 3.
Net returns versus area irrigated.



Curve 3 introduces alternative water sources (R) in equation 4, and shows the most striking effects. Fixed and variable costs are unchanged from curve 2, and irrigation (I) is still that quantity fully adequate to irrigate one unit of land. In addition to I, 20 percent of the water needed to meet full ET requirements is available from other sources (capillary rise, rainfall, and residual moisture). This additional water availability induces a *fall* in yield due to waterlogging and the leaching of nutrients when the area irrigated is less than the 1.2 units that can be fully irrigated by the available sum of irrigation (I) and other sources (R). However, the optimum area irrigated increases substantially, and is relatively stable in the range 2–3 times the area for maximum yield per hectare.

Curve 4 explains a phenomenon observed by Berkoff (1990) in his analysis of irrigation strategies across northern India—beginning in the arid northwest and ending in the moisture surplus east. Stated briefly, a key conclusion of his study is that the management of irrigation becomes progressively more difficult as average rainfall levels increase. With other sources of water meeting 40 percent of the full irrigation requirement, farmers would wish to plant their entire area (curve 4). In this case irrigation is the supplemental source, and short periods without rain induce a demand for irrigation for the entire area. By contrast, in the west, with rainfall much lower, the area planted is already limited by the capacity of the irrigation system, and is thus more consistent with the area that can be subsequently supported in the absence of rain.

In sum, these graphs illustrate, based on a modified version of Hargreaves' formula, a number of commonly observed phenomena. The desired strategy at farm level where land is the limiting resource is to provide full irrigation. Where water is limiting, it will pay to under-irrigate to some degree, especially when input costs are low. If rainfall is significant, under-irrigation will be more attractive, and at a certain point, it is profitable to cultivate all available land since agriculture is rain-fed with irrigation as a supplementary input rather than the other way around. In this last scenario, the appropriate size of an irrigation system will be governed by the relationship between the cost per unit area of irrigation, and the (declining) incremental benefit per unit area that irrigation water adds to rain-fed production.

We recognize that farmers would never deliberately stray to the left of the point at which maximum yield per unit land is achieved. But rainfall is variable (as, all too often, are irrigation supplies!) and thus the risk of oversupply of water as a result of unexpectedly high rainfall is a component of the probability distribution of returns to any particular irrigation strategy that a farmer might choose.

Uncertainty in Irrigation Supply

If a farmer knows precisely how much water will be received, he will aim for the point that maximizes returns to available resources. As argued above, if water is not constrained, the farmer will maximize returns per hectare by delivering that quantity of water that maximizes net value of production per unit land. As water becomes scarce, the farmer will under-irrigate as appropriate to maximize returns to water.

Uncertainty modifies the incentives. Where the optimum returns to water are achieved at a high degree of deficit irrigation, as in figure 3 (curve 3), the farmer risks complete crop failure if there is a shortfall of water, from whatever source, in relation to expectations. On the other hand, if supplies are unexpectedly plentiful, extra water can be productively used to increase net returns.

The farmer can avoid the risk of complete crop failure by reducing the area irrigated and hence increasing the amount of water applied per unit land. In this case, the possibility of shortfalls in supply is a less-serious threat: ET can fall significantly, with commensurate but not disastrous reduction in yield. But unexpected extra supplies are less-well-utilized since ET cannot exceed potential ET_m. Beyond that point, no incremental yield results from the extra water, which will go either to groundwater or to drains or evaporate directly.

Thus the potential profitability of pursuing deficit irrigation is modified by the inherent risk of the approach; creating the potential to exploit unexpected excesses pushes the farmer closer to the point where unexpected deficits threaten complete failure, producing a clear tradeoff in the selection of the area to be irrigated.

We conclude that while conditions of water scarcity induce farmers to practice deficit irrigation, the degree of deficit will be strongly affected by the perceived reliability of supplies. The areas of northern India where the warabandi system is practiced provide the possibility to test these hypotheses.

The Warabandi Principle of Irrigation

The warabandi system has been fully described from a technical perspective (Malhotra 1982) and its underlying philosophy has been very thoroughly explored by Jurriens, Mollinga, and Wester (1996).

In summary, the system was designed to allocate unreliable supplies derived from direct river diversions equitably among all users. Originally applied in colonial India through the Northern India Canal and Drainage Act of 1873, the laws and infrastructure of warabandi remain in place in the Punjab Province of Pakistan, and in India, in the states of Punjab and Haryana, and parts of Rajasthan and Uttar Pradesh.

The system is designed to provide a rationed and equitable service (in proportion to landholding) to all farmers under conditions of extreme water scarcity—the average water available is adequate for full irrigation of about one-third of the command in monsoon and *rabi* (winter) seasons. Rationing and equity are achieved through a three-stage process. First, the larger canals are designed for regulated operation, and are operated in accordance with the availability of water over a wide range of discharges. Offtaking canals are operated in a narrow range, close to full capacity, or are closed. Which canals are closed and which are run, is determined by a published set of "preferences," which rotate every 8 days throughout the season, thus giving every offtaking canal equal probability of receiving water as supplies fluctuate in the parent channels.

Second, below the distributary canals, all channel capacities, and the stream flow in the individual watercourses serving each *chak* (the area within which farmers distribute water—typically 100–400 ha) are proportional to the area served. Thus the water deliveries are uniformly and automatically allocated over the area.

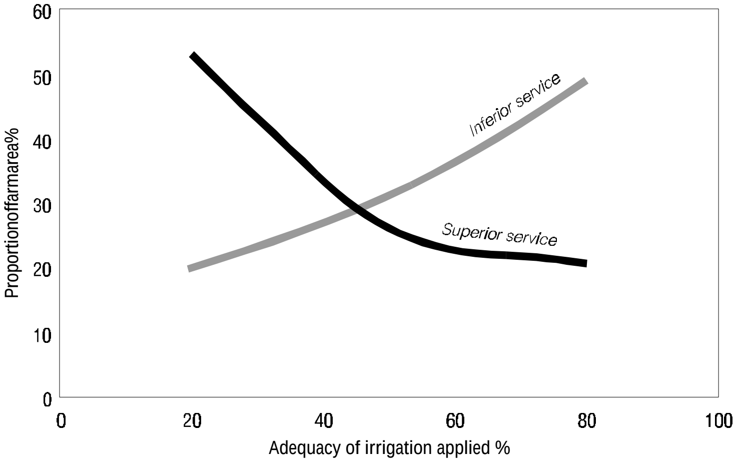
Third, a unique time of the week (starting hour and minute, ending hour and minute) is defined for every farmer within a chak in strict proportion to the area of his holding, thus again giving equity of allocation per unit area.

In sum, the first stage in the process provides an equal probability for any part of the command of receiving or not receiving water in case of shortage; the second stage allocates water uniformly through proportionality of flows per unit service area; and the third stage allocates water uniformly through proportionality of time to farm area.

The procedures remain in place despite dramatic changes in farming and water resource conditions. In the Indian Punjab and Haryana, much of the surface irrigation supplies is now regulated through the construction of massive reservoirs on the Beas and Sutlej (though releases not entirely suited to irrigation requirements continue to be made to meet hydropower demands); groundwater development has reached the point where about half of the water delivered to the fields is from this source (much of this being the recoverable fraction of surface deliveries and infiltration from rainfall); clear yielding varieties predominate.

Since farmers have been accustomed to the system over many years, they highly appreciate the nature of the service. Hence this is an area where we can test the hypotheses developed above to see the extent to which the response of the farmers to the water availability situation is consistent with our expectations for a system in which shortage and uncertainty are prevalent.

FIGURE 4.
Irrigation adequacy and quality of service.



If operated perfectly, the system should, in the long run, give exactly equal supplies to all farmers in terms of both scarcity and certainty. In fact, there are a number of reasons to expect a degree of inequity. First, part of the area is served predominantly by run-of-the-river diversions and cannot deliver water as reliably as the area served by fully controlled reservoir releases. Second, during periods of low deliveries, there is insufficient control at lower levels in the system to allocate water in strict accordance with the rotational preferences—some canals are easier to serve because of the convenient location of a cross-regulator; others have old or inoperative head gates. Third, as in all irrigation systems, powerful farmers attempt to influence the distribution of water through connivance with officials. Finally, it should be noted that the area covered by these systems is enormous (totaling almost 6 million hectares in Punjab and Haryana alone, and would rank as the fifth or sixth largest irrigating "country" in the world!), and thus even with controlled releases from reservoirs, the possibility of deviations from planned deliveries down the thousands of kilometers of canals and tens of thousands of kilometers of watercourses that comprise the system are inevitable.

Thus we can expect that the degree of uncertainty in supplies will vary, and that at least where either human intervention, or systematic bias due to the infrastructure is involved, higher deliveries (more rotational turns) represent greater security of supply.

Fortunately, the observed effect of random extra deliveries will be directly contrary to our hypothesis regarding the farmers' response to increasing certainty. If all farmers have the same expectation of service (volume and certainty), they will all opt for an irrigation intensity consistent with the optimum tradeoff between under-irrigation and risk (figure 3). If supplies are unexpectedly high in a particular area, the observed effect would be that the quantity of water applied per unit area cropped will be *higher* than in the areas receiving normal supplies, and vice versa. However, if the supplies are consistently biased and the areas receiving more water are actually more secure, we will expect to observe farmers following a strategy of *less-intensive* application of water in these areas.

The Study Area

The study area was the command under the Hisar Bhakra Canals Circle (HBC Circle) of the Irrigation Department of the State of Haryana. The canal network in Haryana is divided into four commands, each with its own rostering calendar. There are two sources of supply: Bhakra Dam, from which Haryana draws its share of the flows of the rivers Ravi, Beas, and Sutlej of the Indus river system, and the diversion barrage at Tajewala on the Yamuna River, from which Haryana draws its share of the (uncontrolled) Yamuna flows.

Bhakra storage can be used to supplement the run-of-the-river availability from the Yamuna in parts of Haryana through two link canals, the Narwana Branch and the Bhakra Main Line (BML)-Barwala Link.

The Hisar Bhakra Canals Circle comprises major parts of the BML command and the Barwala-Sirsa command. During the period that the Yamuna brings large flows, mainly in the months May through November, the Sirsa Branch carries part of these flows into the Barwala-Sirsa command (referred to as WYC in the later paragraphs). In the lean period the Sirsa Branch brings in limited flows, and the main source for the command is the diversion from the BML through the BML-Barwala Link. The BML command is supplied exclusively by the tail reach of BML, and enjoys the most stable and predictable supplies among the four commands.

The Canal Network and Command in the Study Area

The command of the Barwala-Sirsa system is underlain with poor quality groundwater, except in a few pockets; poor quality groundwater cannot be used when mixed with canal supplies. In the BML command, the area under the upper half, falling mostly in the HBC Circle, has moderate to good quality groundwater. The soils in the study area are sandy loam increasing in sand content to become sandy soils as one proceeds westward (towards the tail of each system). Total available soil moisture varies from 135 mm/m in the eastern parts to 85 mm/m in the western.

Selection of Sample *Chaks* and Sample Farms

As noted previously, a chak is the area served by one watercourse, typically 200–400 ha, and including 50–100 farmers. Sample chaks were deliberately selected to ensure a wide variation in likely quality of irrigation service, and included chaks served by both the storage-based Bhakra Main Line (BML) system and the run-of-the river Western Yamuna Canal (WYC). Chaks were also selected at various hierarchical levels in the system, and at head, middle, and tail reaches along the parent channel.

Data were collected by the Irrigation Department (ID) officials. The approximate locations for 28 chaks were specified, leaving the final choice to the Superintending Engineer (SE) and his staff, with likely reliability of data as the main criterion for final selection. The final selection was of 24 chaks, 9 served by the WYC, and 15 by the BML.

Among the sample chaks, 9 had no groundwater development as the water was of very poor quality; 7 of these occurred in the WYC command. Eight chaks had groundwater of moderate quality, and this water was usually applied, mixed with surface supplies. Of these, 2 occurred in the WYC command. In the BML command there were 7 chaks in which groundwater was of good enough quality to be applied independently.

In each chak, one holding each at the head, middle, and tail of the watercourse was selected by the official who monitors irrigation by farmers. He recorded information on irrigation and application of other material inputs, mainly fertilizers and pesticides, on each plot in each of the sample holdings. The date of sowing, the dates of irrigation, along with the duration of irrigation, and the dates and amounts of other input applications were recorded.

Data Collected

Data were collected over two consecutive seasons—the monsoon season of 1991 and the rabi season of 1991–92. All data were recorded by Irrigation Department staff amidst their other duties, and were not of uniform quality, especially in the first season. In the second season, a determined effort by the ID staff made it possible to conduct crop-cutting exercises in every sample chak, and the data on water deliveries were also more complete and detailed. These data form the basis for this analysis.

For each plot in the sample farm, an irrigation calendar of the dates of irrigation and the estimated depth of irrigation was prepared. The depth was estimated from the duration of irrigation and the watercourse capacity, with assumed loss of 10 percent between the outlet and the holding in the middle of the chak, and 20 percent between the outlet and the holding in the tail part of the chak. These data are consistent with estimates used for appraisal of the viability of watercourse lining (World Bank 1995).

As there were two crops of importance in rabi, mustard and wheat, with different harvest periods, this needed a substantial effort of field coordination. One mustard field and one wheat field were chosen from each sample farm for estimating yield, using the methodology prescribed by the National Sample Survey Organization of India for crop-cutting exercises.

Data were also obtained on daily discharge at the head of parent channels of the sample chaks, indicating how many full supply turns were provided at the sample outlet, and how many turns of partial supply.

As already noted, in nine of the chaks groundwater was not usable, while in eight the groundwater was of moderate quality so that it could be used, mixed with canal water. Groundwater applications could not be reliably tracked, but with some information on pumping capacity and field enquiries, some estimates could be made of groundwater applied at chaks with mixed irrigation. But no estimates of groundwater (and hence total water) applied could be made at the 7 chaks which had good quality groundwater that could be applied independently of canal water, and data from these were excluded from the analysis.

The analysis was finally based on a sample of 36 wheat plots, and 28 mustard plots, for which full irrigation calendars could be developed.

Data Analysis

The hypotheses being tested relate to farmers' response to scarce and uncertain irrigation supplies. A farmer's decision to pursue deficit irrigation can be demonstrated fairly simply on the basis of water applied (which is a proxy for water availability) in relation to demand, as estimated by the Penman-Monteith formula.

The sample farms were first divided into two groups—those receiving better than average service in terms of irrigation deliveries, and those receiving worse service. Service was defined as the number of full supply turns (defined as turns during which at least 80 percent of the design discharge was maintained for at least 5 days). These criteria are of course somewhat arbitrary, but have the merit of incorporating both volume and stability of supply as part of the criteria. Alternative formulations were explored and gave similar results to those presented below.

Farmers in Haryana receive enough water in each irrigation turn to irrigate only a small proportion of their land.[3] Their approach is to divide their land into a number of plots which are effectively cultivated individually. They then choose, at each turn, which plots to irrigate, and which plots to leave for the next turn. As a result, especially when turns are missed, most farmers end the season with some plots having received more water than others.

TABLE 1.
Distribution of adequacy of water supplied to sample plots.

Adequacy of irrigation applied (%)	Percentage of area at specified adequacy for the total sample	Superior service	Inferior service
<40	37	53	20
40–60	28	26	31
60–100	35	21	49
	100%	100%	100%

We take the following as indicators of the extent of deficit irrigation at the farm level:

- the prevalence of deficit in terms of the percent of an individual farmer's area that is under-irrigated, and
- the degree of under-irrigation observed on that area.

The table below summarizes the observations for the two groups of farmers. The left column indicates the adequacy of irrigation water applied; the second column indicates the percent of farm area in each category of irrigation adequacy for the total sample; and the third and fourth columns show the results separately for the farms with superior and inferior service.

The data indicate the strong general bias towards under-irrigation—only 35 percent of the total area is provided with more than 60 percent of computed irrigation requirements. Further, when the service is better the extent of under-irrigation is higher—only 21 percent of the area where the service is better is provided with more than 60 percent of computed irrigation requirements.

The distribution of these observations is illustrated in figure 4. The Chi-square test indicates a strong association between adequacy of irrigation applied and quality of service at 99 percent level of significance. For 99 percent significance the Chi-square statistic for these data would have to exceed 9.2; the calculated value is more than 25.

We stress again that the observed bias is directly counter to the bias that random variations in service and farmer behavior would produce—better service (more, reliable water) encourages deficit irrigation in pursuit of maximum marginal returns to water. Random availability of surplus water would result in a higher observed level of irrigation adequacy on the areas irrigated.

[3] In a watercourse of 168 ha (for convenience, as there are 168 hours in a week—but not an unusual size), each hectare of land will receive one hour per turn, and the discharge for a watercourse of this area would be about 50 ls^{-1}. Thus the volume delivered per turn per hectare of command is 180 m^3, or a depth of only 18mm. Such a light irrigation cannot be applied using conventional surface techniques, so the farmer irrigates a part of his land (perhaps 20%) to a correspondingly greater depth (90 mm in this case).

Conclusion

The report set out certain hypotheses on how a farmer would decide on area to be sown to a crop and amount of irrigation to allocate to unit area, when the amount of water likely to be available for the entire season is limited. Hypotheses were also stated on how this response might be modified when there is some uncertainty associated with the quantity and timing of irrigation supply.

In any irrigation system, the structures of the uncertainty and the response would be determined by the characteristics of the water resources exploited, and the principle of operation of the system. Data obtained from an irrigation system that has been in operation for many decades under rules for allocation of available water which are reasonably transparent and are largely observed by the operating authority, were analyzed in the context of specific hypotheses that apply to such a system.

The analysis substantially bears out the hypotheses advanced. Farmers generally aim to maximize returns to the scarce resource, but due to the uncertainties involved guard against unacceptable risk of high losses by reducing the area planted and increasing seasonal water allocation per unit area where supplies are less certain.

Literature Cited

Berkoff, D. J. W. 1990. *Irrigation management on the Indo-Gangetic Plain.* World Bank Technical Paper No. 129. Washington D.C.: The World Bank.

Butter, A. 1996. Controlling evapotranspiration and percolation by deficit irrigation. In *Evapotranspiration and irrigation scheduling.* Proceedings of the International Conference, November 3-6, 1996, San Antonio Convention Center, ed. Camp, C. R., E. J. Sadler, and R. E. Yoder, pp.268–274. San Antonio, Texas. St. Joseph, Michigan, USA: American Society of Agricultural Engineering.

Downey, L. A. 1972. Water-yield relations for non-forage crops. *Journal of Irrigation and Drainage Division, American Society of Civil Engineers* 98:107–115.

English, M., and S. N. Raja. 1996. Perspectives on deficit irrigation. *Agricultural Water Management* 32(1):1–14.

English, M. J., J. T. Musick, and V. V. N. Murty. 1990. Deficit irrigation. In *Management of farm irrigation systems,* ed. Hoffman, G. J, T. A. Howell, and K. H. Solomon, pp.631–663. St. Joseph, Michigan, USA: American Society of Agricultural Engineering.

FAO. 1979. *Yield response to water.* FAO Irrigation and Drainage Paper No. 33. Rome: Food and Agriculture Organization.

Hall, W. A., and N. Buras. 1961. *Optimum irrigated practice under conditions of deficient water supply*. Transactions of the ASAE, pp.131–134. St. Joseph, Michigan, USA: American Society of Agricultural Engineering.

Hanks, R. J., H. R. Gardner, and R. L. Florian. 1969. Plant growth-evapotranspiration relations for several crops in the Central Great Plains. *Agronomy Journal* 61:30–34.

Hargreaves, George. 1977. *Water requirements manual for irrigated crops and rainfed agriculture*. Logon, Utah, USA: Utah State University.

Jurriens, M., P. P. Mollinga, and P. Wester. 1996. *Scarcity by design: Protective irrigation in India and Pakistan.* Wageningen, Netherlands: International Institute for Land Reclamation and Improvement. (Liquid Gold 1996 Paper 1).

Jurriens, M., and P. P. Mollinga. 1996. Scarcity by design: Protective irrigation in India and Pakistan. *ICID Journal* 45(2):31–53.

Malhotra, S. P. 1982. *The warabandhi system and its infrastructure.* New Delhi: Central Board of Irrigation and Power.

Sanders, John H. 1997. *Developing technology for agriculture in sub-Saharan Africa: Evolution of ideas, some critical questions, and future research*. Washington D.C.: International Food Policy Research Institute.

Shaozhong, K., and Z. Minggang. 1992. Crop water production function and optimal allocation of irrigation water use. In *Advances in planning, design and management of irrigation systems as related to sustainable land use*: Proceedings of an International Conference, vol. 2, pp.801–807, ed. Feyen, J., E. Mwendera, and M. Badji. Leuven, Belgium: Center for Irrigation Engineering.

Stewart, J. I., and R. M. Hagan. 1973. Functions to predict effects of crop water deficits. *Journal of the American Society of Civil Engineers* (Irrigation and Drainage Division) 99:421–439.

Vaux, H. J. Jr., and W. O. Pruitt. 1983. Crop-water production functions. In *Advances in Irrigation*, volume 2, ed. D. Hillel. Orlando, Florida, USA: Academic Press.

World Bank. 1995. *Appraisal of the Haryana Water Resources Consolidation Project*, Washington D.C.: The World Bank.

Research Reports

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