Analyzing the Impact of Quality and Reliability of Irrigation Water on Crop Water Productivity Using an Irrigation Quality Index

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Introduction

The past 30 years have seen major changes in the criteria for evaluating irrigation systems from the classical irrigation efficiencies to measuring performance using a variety of indicators (see Bastiaanssen and Bos 1999), such as taking into account productivity of irrigation water with the accent on yield (Perry and Narayanamurthy 1998; Sarwar and Perry 2002; Seckler et al. 2003); revenue enhancement per unit of depleted water (Barker et al. 2003); and equity in water distribution (Svendson and Small 1990). As scarcity of irrigation water is becoming evident in many regions and the demand for water increasing from other competing sectors of use (Perry and Narayanamurthy 1998; Amarasinghe et al. 2007), there is a need is to assess the quality of irrigation services in relation to productivity of water rather than in relation to productivity of land (Sarwar and Perry 2002). This means that the factors that need to be taken into account for assessing the quality of irrigation also need to change, the reason being the factors that influence yield are not exactly the same as those which influence water productivity.

The key drivers of change in water productivity are: 1) amount of water depleted in crop production, which changes both the numerator and denominator of productivity parameters; 2) all crop inputs including crop variety, fertilizer and pesticide dosage and labor, which determine the crop yields and net returns, change the numerator of water productivity. Now let us see how the reliability and quality of irrigation affects these drivers and thereby water productivity: It is an established fact that crop yield or biomass production increases in proportion to the increase in transpiration. However, at higher doses, irrigation does not result in beneficial transpiration, but in non-beneficial evaporation. In this way, increased evapotranspiration does not result in a proportional increase in the yield of crops (Vaux and Pruitt 1983). Non-recoverable deep percolation is another non-beneficial component of the total water depleted from the crop land during irrigation (Allen et al. 1998). This also increases at a higher dosage of irrigation.

With greater quality and reliability of irrigation, the farmers might be able to provide optimum dosage of irrigation to the crop, controlling the non-beneficial evaporation and non-recoverable deep percolation. This will result in the consumed fraction remaining low, while the fraction of beneficial evapotranspiration within the consumed fraction (CF) or the depleted water will remain high.[1] Also, it is possible that with a high reliability regime of the available supplies, even under scarcity of irrigation water, the farmers can adjust their sowing time such that they are able to provide critical watering, thereby obtaining high yield responses. Both result in higher water productivity. Furthermore, if more reliable irrigation water is available, farmers would be encouraged to use high yielding varieties, and apply an adequate amount of fertilizers and pesticides to their crops, resulting in better crop yields. Hence, the overall outcome of improved quality and reliability of irrigation would be higher water productivity.

In this paper, the following are attempted: i) developing quantitative criteria for measuring the quality and reliability of irrigation water at the farm level that will capture the complex physical variables relating to irrigation and affecting crop water productivity; ii) assessing the impact of quality and reliability of irrigation on water productivity in agriculture, through an analysis of individual crops; and iii) analyzing the factors that cause differential water productivity, which change due to change in quality and reliability regime.

Review of Literature on Analyzing the Performance of Irrigation Systems

Lately, irrigation researchers worldwide have begun to show a keener interest in trying to develop indicators for measuring the performance of irrigation systems and also to assess the impact of different irrigation management strategies on crop yields and productivity of land and water quantitatively, in view of the growing shortage of irrigation water, and the competing demands for water from other sectors. Four main strategies which were examined are: 1) providing deficit irrigation; 2) improving the timeliness of irrigation; 3) precision irrigation; and 4) improving the quality and reliability of irrigation. One of the motivating factors behind this is to identify the best strategy for improving the performance of irrigation systems, given its potential as a powerful tool to manage the demand for water in agriculture.

Svendson and Small (1990) analyzed the farmers' perspective of irrigation system performance. They found that the way farmers evaluate the performance of irrigation systems is by mainly focusing on the outcome and impact of the irrigation systems, and not so much by the process involved in managing irrigation such as staffing policies of the agency, pattern of communication and nature of farmers' participation in water users associations. According to Svendson and Small (1990), the ten important measures that farmers would use to assess irrigation system performance are: depth related measures viz., adequacy, equity and timeliness; farm management related measures such as tractability, convenience and predictability; and water quality related measures viz., temperature, sediment content, nutrient content; toxins and pathogens. But, how these criteria could be converted into normative indicators for analyzing irrigation system performance, or even strategies for improving the same were not addressed.

[1] See Allen et al. (1998) for detailed discussion on various components of the applied water, such as consumed water, consumed fraction, beneficial transpiration, non-beneficial evaporation from the soil and non-recoverable deep percolation.

Bastiaanssen and Bos (1999) argued that a new generation of irrigation performance indicators such as adequacy, equity and productivity could be quantified using remote sensing data, based on previous work by several scholars such as Azzali and Menenti (1987), Bastiaanssen (1998), Menenti et al. (1989), Moran (1994), Roerink et al. (1997). For instance, Menenti et al. (1989) measured equity in irrigation water distribution by evaluating the actual flow per unit of irrigated area, at different spatial scales, in which the irrigated area was measured using satellite data. Moran (1994) used vegetation index and surface temperature to assess the adequacy. Bastiaanssen (1998) expressed adequacy in irrigation as a ratio of the total energy consumed by the crop in the form of ET and the total energy available for ET, and computed it from the surface energy balance. The study argued that equity in irrigation performance could be evaluated by taking a digital overlay of the Solar Energy Balance (SEB), with administrative boundaries and calculating the coefficient of variation across space. Roerink et al. (1997) extended the ET fraction approach used by Bastiaanssen (1998) and calculated the coefficient of variation of actual ET over total water supplied to quantify productivity.

Anecdotal and research based evidences of differential productivity gains in well irrigation over canal irrigation vis-à-vis yield and water productivity exist. This gain has been attributed to virtues of well irrigation over canal irrigation such as timeliness, greater quality in terms of adequateness and control over water delivery (Chakravorthy and Umetsu 2004; IRMA/UNICEF 2001; Kumar and Singh 2001). Some empirical studies showed the positive impact of the timeliness of irrigation on paddy yields in the canal command areas (Meinzen-Dick 1995). Other studies showed higher yield and net returns for crop production in diesel-engine irrigated crops over electric-pump irrigated ones (Kumar and Patel 1995), with the difference being attributed to better access to and control over irrigation, being possible with diesel-engine operated wells, i.e., the ability of the farmers to irrigate the crop as and when required, or better 'timeliness'.

Studies in Pakistan Punjab showed that farmers who used conjunctive irrigation in canal command areas obtained greater yields than those who used only canal water for their wheat and rice crops (Hussain et al. 2003). A study by Sarwar and Perry (2002) in the Indus Plains of Pakistan, which simulated crop growth and ET under different irrigation schedules by using SWAP (Soil-Water-Atmosphere-Plant) model, showed that it is possible to enhance crop water productivity through deficit irrigation. The study showed 47 % higher crop water productivity under deficit irrigation conditions as opposed to unrestricted irrigation supply conditions, which led to the conclusion that while applying water to meet the exact crop water requirement would be the right strategy under situations of plentiful water, as regards in situations of scarcity, restricted water supply would be the strategy to maximize the productivity of water. Nevertheless, whether irrigation is in a deficit regime or in a water surplus regime is highly crop specific. And, as such, actual impacts on crop production cannot be assessed realistically, unless the farmers' responses in terms of crop choices are also modeled.

According to another analysis by Perry and Narayanamurthy (1998), rationing irrigation to make it available during critical stages, which corresponds to crop growth stages where yield sensitivity to ET is high, is a useful strategy in enhancing crop yields. However, there are practical problems in assessing the quality of irrigation in terms of water availability during critical stages, and then applying it to devise an appropriate water delivery policy for an irrigation scheme. First, the farmers' sowing time for crops varies significantly within the same irrigation command, and thereby changes the timing for critical waterings across the farms. Second, farmers in many irrigation systems in Asia grow multiple crops with the result that the critical stage with respect to 'growth response to ET' differs widely. Moreover, the quality of irrigation available from an irrigation system cannot be assessed in relation to water availability during the critical stage alone.

In a nutshell, the review of available irrigation literature shows that the studies cover either an analysis of different indicators for assessing irrigation system performance from different perspectives (farmers and irrigation agencies; use of different scientific methodologies to assess the performance of irrigation schemes in terms of crop yields or crop growth) or different approaches to improve the performance of irrigation systems in terms of their outcomes, under a set of conditions existing in the field vis-à-vis crops and climate. If not, there are mere qualitatively analysis of the impact of quality of irrigation on crop yields. But, it is important to note here that the real field outcomes of introducing irrigation management strategies suggested by such crop growth-based econometric models (see for instance, Perry and Narayanamurthy1998) would deviate far from the model predictions. This is due to the reason that such models fail to take into account the farmers' decision-making variables with regard to crop choices under different irrigation water supply regimes. Most of the studies assess productivity in relation to land.

Such studies, therefore, leave major information gaps about the governing parameters that can be manipulated for the performance improvement of irrigation systems, which are also crucial for working out their operational policies. There is hardly any empirical research that attempts to develop quantitative criteria, which use measurable physical indicators, for assessing the quality and reliability of irrigation and to capture complex variables such as the timeliness of irrigation, physical access to irrigation water source, water delivery rates and control over water delivery.[2] Such quantitative measures are important for working out operational policies for irrigation management.

Furthermore, very little is known about how improved quality and reliability of irrigation cause differential productivity, and the extent to which such factors contribute to water productivity changes. Instead, best known are the physical processes involved in plant growth, and the manner in which that changes with irrigation. But, what is needed is the real life impacts of different irrigation management interventions like improving 'quality and reliability' of irrigation on productivity of water.

The Study Objectives and Methodology

Study Location

In the Bist Doab area of Punjab, the climate varies from semi-arid to hot, sub-humid from south-west to north-east (Hira and Khera 2000). The Bist Doab area provides a unique opportunity to analyze the impact of the reliability of irrigation on crop yields and water productivity, the reason being the presence of farmers using canal water, groundwater and

[2] This does not ignore the fact that several scholars had highlighted the need for improving the timeliness or irrigation on crop yields (Meinzen-Dick 1995); providing watering at critical stages of crop growth (Perry and Narayanamurthy 1998); and deficit irrigation under situations of water scarcity as crucial factors in enhancing productivity (Sarwar and Perry 2002).

both in the same location with a similar agro-climate. Also, incidentally, there are pockets where reliability of canal irrigation is quite high, against locations which are traditionally known for poor quality canal irrigation, overcoming the problem of wrongly attributing differential productivity to a particular source of irrigation.

One of the locations (Changarwan Village) chosen for the study in Hoshiarpur District receives an adequate amount of canal water from the Shah Neher Canal. Very few farmers have wells, and are located outside the command. But, farmers who receive canal water do not practice well irrigation. The area, which is part of the sub-mountainous region of Punjab, receives nearly 900 mm of rainfall, and is hot and sub-humid. The second location (Skohpur Village) located in Nawanshehr District is well known for intensive well irrigation, and the canal water supply is generally poor, except in very good rainfall years. The area receives a mean annual rainfall of approximately 450 mm (source: based on Hira and Khera 2000). Most of the farmers who receive canal water also practice well irrigation, at least for some crops.

Objectives

The overall objective of this paper is to analyze the impact of quality and reliability of irrigation water on the water productivity of crops. This is done by comparing the physical productivity of water and water productivity in economic terms for individual crops, under different types of irrigation systems with differential quality and reliability.

The specific objectives are to: 1) Develop a composite index for quality and reliability of irrigation water, that is relevant for three different types of irrigation systems, viz., canal irrigation, well irrigation and conjunctive method of irrigation, at the field scale; 2) Estimate the values of the index for the irrigation water supply condition in two locations in Bist Doab area; 3) Analyze the impact of quality and reliability of irrigation water on crop water productivity and cropping pattern in the Doab area; and 4) Analyze the factors responsible for differential productivity of water use in crop production.

Methodology, Data and Sampling

The quality and reliability of irrigation would influence water productivity in many different ways. First, good quality and reliable irrigation services would provide farmers with the opportunity of optimizing the dosage of irrigation, which can help prevent the non-beneficial evaporation of soil moisture from the field during the crop development stages and residual moisture in the soil after the crop harvest, thereby bringing the depleted water close to beneficial ET. Reliable and quality irrigation would motivate farmers to use fertilizers adequately, use high yielding seed varieties, invest in agronomic practices and also go for high-valued crops that involve more risk. This would positively affect the yield. Since, differential input costs need to be factored in the productivity analysis, the combined physical and economic productivity of water also needs to be compared. Furthermore, since the cropping pattern might change from one source to another, overall net water productivity (Rs/m^3), including all the crops, needs to be compared for understanding the real impact of improved quality and reliability of irrigation.

Since there are perceptible differences in the quality and reliability of irrigation between canal irrigation and well irrigation, and also between well irrigation and conjunctive use, the impact of reliability and quality on water productivity can be compared by comparing the field level water productivity of applied water for the same crop for these different sources (both in

Kg/m^3 of applied water and Rs/m^3 of applied water). But, it is also important to quantify the quality and reliability of irrigation using certain realistic criteria based on physically measurable indicators. Then the productivity values for different sources can be compared against the estimated values of quality and reliability of the source.

In order to analyze the factors responsible for differential water productivity, or identify the determinant of water productivity that changes with quality and reliability of irrigation, the data on crop inputs viz., labor use, fertilizer and pesticide use were analyzed for all the farms and the mean figures were compared.

The sample size for Changarwan Village is 36, 18 each of farmers using canal irrigation and well irrigation supply. In case of Skohpur Village the sample size is 35, of which 21 farmers use well irrigation and 14 farmers have adopted the conjunctive use method. Among these, there are three farmers who for certain crops use only canal water supply for irrigation.

Primary data were collected from the sample farmers, in both locations using real time monitoring. The data collected included: area under different irrigated crops; date of sowing and harvesting; the actual irrigation schedules, including the timing and duration of each watering; crop outputs; the price of produce (price at which it is being procured by the Food Corporation of India); the discharge of pumps; and the canal discharge rate.

Analytical Procedure

The differential quality and reliability of irrigation vis-à-vis a crop can be quantitatively estimated by using certain irrigation related physical parameters. They are: water control index; number of irrigations; average duration per watering per unit cropped area; and maximum time duration between two waterings during the entire crop season.

It is argued here that higher frequency improves the quality and reliability of irrigation. The reason is that a greater frequency of irrigation reduces the chances of moisture stress. Also, the greater the duration of watering, the better would be the quality. Greater duration of water delivery would enhance the chances of improving field application efficiency. On the contrary, greater the time gap between two farmers watering for the same crop, the poorer would be the quality of irrigation and greater would be the chances for crop damage due to water stress. The correct dosage of water, by maintaining the delivery rate, could prevent the leaching of fertilizers and other nutrients in the soil, thereby maintaining good growth.

Quality and reliability of irrigation for wells, canals and conjunctive use for a farmer *l*, with respect to a given crop is assessed in terms of an irrigation quality index (δ_l) defined by

$$\delta_l = \frac{In_l \, Id_l \psi_l}{t_l} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

$$\psi_l = [\, aq - bq_l^2 \,] \text{ where, } a = 0.13 \text{ and } b = 0.0026$$

Where ψ_l is the water control index for farmer *l*, ln_i and ld_i are the number of times of irrigation and duration of irrigation (hr/ha), respectively, given by the sample farmer *l* for a crop; t_l is the maximum time duration between any two consecutive waterings given by sample farmer *l* for the crop in days. q_l is the rate of water delivery (l/s) for that farmer. It is assumed that a water delivery rate of 15 liters per second is best for the crop for which the index would be one and accordingly the values of coefficients *a* and *b* were estimated.[3]

From the index δ obtained for each farmer in the sample, the mean values would be estimated and compared against the field level water productivity.

The detailed analytical procedure employed for estimating water productivity parameters is available in Kumar et al. (2008).

The computed value of irrigation quality index can be interpreted as higher the value of the index, higher is the quality and reliability of irrigation water delivered to a given field.

Results and Discussion

Irrigation Quality Index for Different Irrigation Systems

Based on real time data on irrigation schedules, duration of irrigation and the water delivery from the source, the irrigation quality (IQ) index was estimated for all the sources, viz., well irrigation, conjunctive irrigation and canal irrigation. The estimates for Changarwan are provided in Table 1 and that for Skohpur are provided in Table 2. As Table 1 shows, the IQ value is higher for well irrigation for all crops except paddy. This is understandable. In the case of wells, for a given crop, the number of irrigations was much higher. Also, the time gap between two consecutive watering was lower. In the case of paddy, the value of the index is slightly higher for canal irrigation.

Table 1. Estimates of irrigation quality index for canal irrigation and well irrigation at Changarwan (Zone 1) for selected crops.

Name of Season	Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)
Kharif	Paddy	Well	2.66
		Canal	3.33
	Maize	Well	10.28
		Canal	0.65
	Bajra	Well	1.37
		Canal	0.25
Winter	Wheat	Well	2.26
		Canal	0.5
	Barseem	Well	0.44
		Canal	0.17

Source: Authors' own analysis based on primary data

[3] The relationship between q and ψ was assumed to be convex, defined by a quadratic equation. The highest value of the water delivery index was assumed to be 'one' at the delivery rate of 15 liters per second. At that level, the slope, i.e., differential d ψ_I/d q will be zero.

In the case of Skohpur, there are three sources of irrigation, i.e., well, canal and conjunctive use. The computed values of IQ are higher for well irrigation except for kharif bajra and maize. For maize, the IQ value is highest for conjunctive irrigation, and in the case of bajra the value is highest for canal irrigation.

Table 2. Estimates of quality and reliability for well irrigation, canal irrigation and conjunctive use at Skohpur (Zone 2) on selected crops.

Name of Season	Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)
Kharif	Paddy	Well	26.77
		Canal	13.51
		Conjunctive	28.16
	Maize	Well	2.63
		Canal	2.2
		Conjunctive	5.01
	Bajra	Well	1.44
		Canal	2.29
		Conjunctive	1.16
Winter	Wheat	Well	1.05
		Canal	0.87
		Conjunctive	1.25
	Barseem	Well	1.43
		Canal	1.17
		Conjunctive	0.32

Source: Authors' own estimates based on primary data

Water Productivity of Different Crops

The mean value of crop yields, and estimated mean value of irrigation dosage, and water productivity in physical and economic terms for the major crops viz., paddy, maize, bajra, wheat and barseem for well irrigated crops and canal irrigated crops are presented separately in Tables 3 and 4. Comparing crop yields between irrigation sources show higher yield values for canal irrigated fields. The comparison shows the following: 1) the irrigation dosages are much higher for canal-irrigated fields for all five crops mentioned above; 2) physical productivity of water is higher for well-irrigated fields, for paddy, maize and wheat; and 3) the values of water productivity in economic terms are higher for well- irrigated fields for maize, bajra and wheat.

The irrigation dosages are excessive for fields which are receiving canal water. Even so, the yields are much higher for these fields when compared to well-irrigated fields in spite of the fact, that the well irrigated fields are getting adequate quantities of water. One important reason for these differences in yield viz., canal irrigation is the chemical quality of the canal water. As reported by the farmers in Changarwan Village, the canal water that comes from the

Bhakra irrigation scheme in Punjab-Himachal border is very rich in many minerals present in its hilly catchments in the Shivalik hills. The continuous availability of this water for the past four decades had made the land receiving this water also very fertile. Hence, the nutrient regime in the soil is much higher in the canal irrigated fields.

Table 3. Water productivity estimates of different crops under well irrigation at Changarwan (Zone 1).

Well Irrigation					
Name of Crop	Total Irrigation Water Applied [m³/acre]	Crop Yield [kg/acre]	Net Income [Rs/Acre]	Water Productivity in Main Product [kg/m³]	Water Productivity [Rs./m³]
Paddy	3,518.5	1,169.5	548.8	0.57	0.32
Maize	598.7	941.7	1,629.3	1.53	6.44
Bajra	1,497.9	6,025.0	3,425.5	7.82	0.43
Wheat	915.4	1,003.6	754.1	1.97	4.45
Barseem	1,184.5	4,864.6	9,474.0	1.72	12.99

Source: Authors' own estimates based on primary data

Table 4. Water productivity estimates of different crops under canal irrigation at Changarwan (Zone 1).

Canal Irrigation					
Name of Crop	Total Irrigation Water Applied [m³/Acre]	Crop Yield [kg/Acre]	Net Income [Rs/Acre]	Water WaterProductivity in Main Product [kg/m³]	Productivity [Rs/m³]
Paddy	5,849.8	1,661.2	6,183.8	0.41	1.50
Maize	2,600.0	880.0	4,336.2	0.53	2.00
Bajra	1,935.8	8,122.2	7,358.2	10.41	0.09
Wheat	1,109.0	1,100.6	2,465.4	1.57	3.46
Barseem	2,488.5	7,216.7	16,454.0	3.60	24.01

Source: Authors' own estimates based on primary data

The mean value of crop yields, estimated irrigation dosage, and estimated water productivity in physical and economic terms for the major crops irrigated by wells, canals and conjunctive method in the Skohpur Village are presented separately in Tables 5, 6 and 7, respectively. Comparison across sources shows the following: 1) the depth of irrigation is highest for fields irrigated by canals, followed by conjunctive use, and lowest for wells i.e., for paddy and wheat; 2) the yield is higher for well irrigated fields for paddy and barseem, whereas it is higher for canal irrigated fields in the case of maize; 3) the physical productivity of water is higher for well irrigated fields in the case of paddy, bajra and wheat, and highest for canal irrigated fields in the case of maize. As regards water productivity in economic terms, values were higher for well-irrigated fields for all crops except bajra.

Table 5. Water productivity of different crops under well irrigation at Skohpur (Zone 3).

Well Irrigation					
Name of Crop	Total Irrigation Water Use [m³/Acre]	Crop Production [kg/Acre]	Net Income [Rs/Acre]	Water Productivity in Main Product [kg/m³]	Water Productivity [Rs/m³]
Paddy	4,548.0	2,270.0	12,520.7	0.79	4.46
Maize	1,381.0	1,060.0	310.3	3.30	6.34
Bajra	1,040.9	5,607.8	-244.40	17.21	0.37
Wheat	697.5	1,494.1	8,584.8	3.41	19.80
Barseem	3,050.6	6,214.3	12,676.8	3.52	30.28

Source: Authors' own estimates based on primary data

Table 6. Water productivity estimates of different crops under canal irrigation at Skohpur Village (Zone 3).

Canal Irrigation					
Name of Crop	Total Irrigation WaterApplied [m³/Acre]	Crop Production [kg/Acre]	Net Income [Rs/Acre]	Water Productivity in Main Product [kg/m³]	Water Productivity [Rs/m³]
Paddy	11,722.6	1,766.7	3,966.2	0.20	0.06
Maize	2,836.1	1,260.0	6,656.4	9.15	1.99
Bajra	6,433.6	4,500.0	1,752.2	1.45	1.03
Wheat	1,787.0	1,592.9	9,820.0	2.37	14.32
Barseem	2,382.3	5,400.0	11,263.7	2.41	10.56

Source: Authors' own estimates based on primary data

Table 7. Water productivity estimates of different crops under conjunctive use of irrigation at Skohpur Village (Zone 3).

Conjunctive Use					
Name of Crop	Total Irrigation WaterApplied [m³/Acre]	Crop Production [kg/Acre]	Net Income [Rs/Acre]	Water Productivity in Main Product [kg/m³]	Water Productivity [Rs/m³]
Paddy	7,740.0	2,188.9	11,628.3	0.79	4.19
Maize	1,247.4	783.3	1,635.8	0.73	1.50
Bajra	475.20	8,600.0	4,400.0	9.05	4.38
Wheat	1,745.0	1,518.3	9,528.8	2.51	16.99
Barseem	3,909.6	5,675.0	8,869.40	3.76	9.73

Source: Authors' own estimates based on primary data

Relationship between Quality and Reliability of Irrigation and Water Productivity of Crops

Table 8 shows the estimates of irrigation quality index (IQ) for five major crops under two major sources of irrigation, viz., wells and canals, and the corresponding estimates of physical and economic productivity of water for these crops for Changarwan Village. It can be seen that in situations where the irrigation quality index is higher, the water productivity in economic terms is higher as well. The only exception is barseem. Another interesting observation is that water productivity in economic terms does not follow the same trend as that of physical productivity of water. The physical productivity of water was found to be higher for fields, which have lower irrigation quality index, e.g., paddy, bajra and barseem.

One reason for this could be the difference in duration of the crop between fields under different sources of irrigation. In crops such as bajra and barseem where only leafy biomass is harvested, if water is available in plenty through excessive water delivery, farmers might take more harvests of these fodder crops with a greater number of irrigations. This would reduce the value of IQ, but may not reduce the physical productivity of water as the biomass output would increase in proportion to the amount of water used.

Table 8. Productivity of water for crops at Changarwan (Zone 1).

Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)	Water Productivity (kg/m^3)	Water Productivity (Rs/m^3)
Paddy	Well	2.66	0.57	0.32
	Canal	3.33	0.41	1.50
Maize	Well	10.28	1.53	6.44
	Canal	0.65	0.53	2.00
Bajra	Well	1.37	7.82	0.43
	Canal	0.25	10.41	0.09
Wheat	Well	2.26	1.97	4.45
	Canal	0.5	1.57	3.46
Barseem	Well	0.44	6.53	12.99
	Canal	0.17	10.23	24.01

Source: Authors' own estimates based on primary data

Table 9 shows the estimates of irrigation quality index for five major crops under well irrigation, canal irrigation and conjunctive use, and the corresponding estimates of physical productivity and economic productivity of water for these crops for Skohpur Village. Similar to what was seen in the case of Changarwan, comparing well irrigated crops and canal irrigated crops in Skohpur shows that water productivity (Rs/m^3) was found to be higher for fields, which have higher irrigation quality and reliability, except for paddy.

Table 9. Productivity of water for crops at Skohpur (Zone 3).

Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)	Water Productivity (kg/m^3)	Water Productivity (Rs/m^3)
Paddy	Well	26.77	0.79	4.46
	Canal	13.51	0.20	0.06
	Conjunctive	28.16	0.79	4.19
Maize	Well	2.63	3.30	6.34
	Canal	2.2	9.15	1.99
	Conjunctive	5.01	0.73	1.50
Bajra	Well	1.44	17.21	0.37
	Canal	2.29	1.45	1.03
	Conjunctive	1.16	9.05	4.38
Wheat	Well	1.05	3.41	19.80
	Canal	0.87	2.37	14.32
	Conjunctive	1.25	2.51	16.99
Barseem	Well	1.43	3.33	30.28
	Canal	1.17	2.41	10.56
	Conjunctive	0.32	2.02	9.73

Source: Authors' own estimates based on primary data

Impact of Quality and Reliability of Irrigation Water on Drivers of Change in Crop Water Productivity

We have begun our analysis with the premise that improved quality and reliability of irrigation, expressed in terms of irrigation quality index (IQ), would be able to manipulate the water productivity parameters through controlling the major drivers of change in water productivity such as irrigation dosage, fertilizer and pesticide inputs.

Increase in irrigation dosage, to a great extent, increases the beneficial evapo-transpiration from the crop and, therefore, the crop yield. But, excessive irrigation will not have any positive effect on crop yields. On the other hand, it increases the denominator value of water productivity. We have seen that the IQ values are much higher for well-irrigated fields of both locations. Similarly, for most crops in Changarwan, the irrigation dosages are much lower for well-irrigated fields than for canal-irrigated fields. The trend was the same in the case of Skohpur. The irrigation dosage was much higher in the canal irrigated fields and in the fields irrigated by both canals and wells, than that of well-irrigated fields for most crops samples of Sokhpur Village.

This means that the highest influence of IQ is in controlling the water delivery in the field. A lower IQ meant a higher dosage of irrigation and vice versa. Actually, lower number of irrigations and shorter durations of watering, which have a negative effect on the dosage of irrigation, reduce the value of IQ. But, the only factor which actually increases the dosage of irrigation is the excessively high discharge rate, which reduces the value of the water control index. For instance, in the case of canal irrigated fields in Skohpur, the discharge rates measured were in the range of 54 m^3/hour to 136.8 m^3/hour, whereas the discharge rate varied from 35.46 to 67.9 m^3/hour for wells (source: field level measurements).

Excessive dosage of irrigation is likely to reduce both the physical and economic productivity of water. But, fertilizer and pesticide dosage and labor input are also other drivers of change in water productivity as they can increase the yield, without changing the denominator of water productivity in kg/m^3. Generally, their effect on the physical productivity of water would be positive. At the same time, these inputs can increase the cost of production significantly and, therefore, its marginal impact on the net returns may not be always positive. We have begun our analysis with the assumption that better quality and reliability in irrigation services would lead to optimal use of other inputs such as fertilizers, pesticides and labor.

Comparative analysis of crop inputs such as fertilizer, pesticide and labor use between crops which receive irrigation of differential quality and reliability does not fully support this hypothesis. In Changarwan, for instance, the change in levels of fertilizer and pesticide dosage with the change in source of irrigation was found to be significant only for paddy, wheat and maize. What emerges from the comparison is that the dosage of these inputs does not increase with the increase in irrigation quality index (Table 10). The canal-irrigated fields, which get less reliable supplies, do not necessarily receive a lower dosage of fertilizer and other inputs. One reason for this could be that as the irrigation dosage is very high in the case of canal-irrigated fields resulting in heavy percolation, farmers provide for leaching of fertilizers, which occur due to it. Another reason could be that quality and reliability does not matter so much for fodder crops such as bajra and barseem, and that farmers try to obtain higher yield through a higher dosage of inputs.

Table 10. Comparison of input use and water productivity in economic terms at Changarwan Village (Zone 1).

Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)	Input Use (Rs/Acre)		Labor (Rs/Acre)	Water Productivity (Rs/m^3)
			Fertilizer	Pesticide		
Paddy	Well	2.66	607.8	179.0	1,393.81	0.32
	Canal	3.33	701.5	157.0	1,207.37	1.50
Maize	Well	10.28	566.3	135.5	333.3	6.44
	Canal	0.65	272.3	196.2	666.6	2.00
Bajra	Well	1.37	215.0	-	1,200	0.43
	Canal	0.25	242.9	-	-	0.09
Wheat	Well	2.26	629.1	176.0	918.6	4.45
	Canal	0.5	775.5	169.8	944.6	3.46
Barseem	Well	0.44	438.5	120.0	560	12.99
	Canal	0.17	426.5	350.0	300	24.01

Source: Authors' own estimates based on primary data

A significant difference in labor use was found between sources for three crops viz., paddy, maize and barseem. Here, contrary to what was generally perceived, labor input was higher for fields which received irrigation water of lower reliability.

Analysis for Skohpur (Table 11) shows that there is no general pattern in the input use vis-à-vis source of irrigation or quality and reliability of irrigation. Similarly, in the case of labor input also, no general pattern is seen to be emerging. As a result, lower quality and reliability of irrigation does not necessarily result in lower water productivity in physical terms but in economic terms, as shown by a majority of the cases from both the field locations.

Table 11. Comparison of input use and water productivity in economic terms at Skohpur Village (Zone 3).

Name of Crop	Irrigation Quality Index (IQ)	Source of Irrigation	Input Use (Rs/Acre)		Labor (Rs./Acre)	Water Productivity (Rs./m^3)
			Fertilizer	Pesticide		
Paddy	26.77	Well	1,004.9	151.9	1,032.0	4.46
	13.51	Canal	857.70	245.7	1,195.2	0.06
	28.16	Conjunctive	1,019.4	196.0	1,047.6	4.19
Maize	2.63	Well	954.0	228.4	1,201.2	6.34
	2.2	Canal	1,058.7	148.9	966.6	1.99
	5.01	Conjunctive	1,007.3	178.3	281.5	1.50
Bajra	1.44	Well	345.0	-	845.0	0.37
	2.29	Canal	500.0	55.0	500.0	1.03
	1.16	Conjunctive	-	-	-	4.38
Wheat	1.05	Well	835.2	199.2	824.8	19.80
	0.87	Canal	1,080.7	206.7	727.7	14.32
	1.25	Conjunctive	875.9	165.6	1,300.0	16.99
Barseem	1.43	Well	535.9	-	-	30.28
	1.17	Canal	591.0	495.0	466.6	10.56
	0.32	Conjunctive	675.0	175.0	-	9.73

Source: Authors' own estimates based on primary data

Impact of Differential Quality and Reliability of Irrigation Water on the Cropping Pattern

The quality and reliability of irrigation had some impact on the cropping pattern chosen by the farmers. The area allocated by well irrigators for maize during kharif was higher in Changarwan as compared to canal irrigators (see Tables 12 and 13). Obviously, maize consumes far less water when compared to paddy; however, it is not a highly water-efficient crop. There are two reasons for the greater preference for maize. One is the water shortage during summer

Table 12. Comparison of cropping pattern at Changarwan Village (Zone 1).

Name of Crop	Percentage area under source	
	Well	Canal
Paddy	31.41	43.41
Maize	11.42	2.37
Bajra(GF)	5.21	7.14
Wheat	44.85	42.15
Barseem	5.93	4.90

Source: Authors' own estimates based on primary data

Table 13. Comparison of cropping pattern at Skohpur Village (Zone 3).

Name of Crop	Percentage area under source		
	Well	Canal	Well + Canal
Paddy	24.1	9.99	48.90
Maize	18.5	25.8	7.52
Bajra (GF)	4.56	8.43	1.25
Wheat	42.3	44.5	28.5
Barseem	6.72	10.2	4.7

Source: Authors' own estimates based on primary data

months induced by a restricted power supply in the farms[4] and the other is the high cost of diesel required for pumping groundwater. This makes paddy production with diesel-pump irrigation an unattractive proposition for the farmers. But, the canal irrigators in the same village (Changarwan) get plenty of canal water for paddy, with good reliability as seen from the estimates of quality and reliability of canal water supply for paddy in that village. Hence, they are able to allocate more land for paddy.

In the Skohpur Village the reliability of canal water supply is very poor. This is indicated by the figures of irrigation quality and reliability index estimated for canal water supplies for paddy, which have been subsequently confirmed during discussions with farmers. The lower reliability of canal water supplies is forcing farmers to allocate a smaller area for water-intensive paddy. The main reason for this is that the returns from paddy are dependent on the adequacy of irrigation water applied, as seen from the comparison of net returns from paddy. While the well irrigators get net returns of Rs.12,000 from an acre of paddy, the canal irrigators get only Rs.3,900 per acre in that village. Hence, we could infer that quality and reliability of water influences the cropping pattern wherein the farmers choose crops that give a higher return from every unit of land they cultivate, if quality and reliability of irrigation water is good.

[4] In Punjab, monsoon arrives in the first week of July, while the transplanting of paddy starts in June itself. During the month of June, the potential evapotranspiration of the crop rapidly goes up due to very high temperatures and high aridity, and the crop needs frequent waterings (Hira and Khera 2000).

Conclusions

In our research, we have developed quantitative criteria for assessing the quality and reliability of irrigation water at the field scale, and using these criteria, a composite index called the irrigation quality index was developed. The index uses the water control index, a function of water delivery rate; the frequency of irrigations; the duration of irrigation; and the maximum time gap between two consecutive waterings as the determinants. The values of the index are computed with reference to a crop, and hence the values obtained for two different crops are not comparable. The values of the index were worked out at the field level under three different sources of irrigation in the Bist Doab area.

The estimates of irrigation quality index were found to be higher for well irrigated fields as compared to canal irrigated fields and fields irrigated by both wells and canals in Skohpur Village. But, the same were found to be higher for canal irrigated fields in the case of the Changarwan Village for paddy. This is in confirmation with what the farmers in these villages perceive about the quality and reliability of irrigation water deliveries from canals from the respective villages. Hence, we could conclude that the quantitative criteria evolved for estimation of this composite index are realistic.

Comparison of the values of irrigation quality index estimated for major crops under different sources of irrigation vis-à-vis the water productivity of the respective crops show that differential reliability has an impact on economic productivity of water (Rs/m^3). The fields, which received irrigation water of higher quality and reliability, got higher water productivity in Rupee terms. But, the impact of differential quality and reliability was not manifest in the physical productivity of water for fodder crops.

The findings of our research contradict the conventional wisdom that higher quality and reliability of irrigation would result in better yields at least for one location, i.e., Changarwan. But, the deviation found in this case could be due to the differences in the chemical quality of water, which the index could not capture. Nevertheless, one can conclude that improved quality and reliability of irrigation would help enhance the water productivity in crop production. The research also showed that quality and reliability of irrigation water also had a significant impact on the cropping pattern. Nevertheless, the index developed here is not adequate to assess the IQ of crops, which can be harvested many times during the crop season. Also, the irrigation quality index needs refinement so that it could account for differences in the chemical quality of irrigation water.

Policy Inferences

The research gives sufficient indications to irrigation water policymakers in India on the need to invest in improving the quality and reliability of water supplies from the schemes, be it public irrigation systems like canals or private irrigation systems like wells. It also shows that the parameters that need to be manipulated to improve the quality and reliability of irrigation water are frequency of irrigation, duration for which water is available to the field, and discharge rate. The frequency of irrigation has to increase; the time gap between two waterings has to reduce; the duration for which water is available to the field has to increase; and the discharge has to be moderate, not too low and not too high.

In the case of public canals, achieving this would call for major changes in the paradigm of the irrigation scheme design itself. For instance, reducing the discharge rate for the water courses would mean reducing the size of the chak[5] itself, which is normally of 40 ha. In order to increase the frequency of water delivery, it is important that the minors run at the full supply level throughout the season. The success of it again would depend on whether the scheme has got adequate amount of water or not. But, in the short and medium term, what is achievable is the creation of intermediate storage systems below the delivery outlets (minor outlets) so as to enable the farmers to use the water as and when needed in a controlled way. By doing this, three important parameters governing quality and reliability of irrigation, viz., frequency of watering, duration of water supply and water delivery rate could be manipulated at the field scale. Nevertheless, in the irrigation command having wells, quality and reliability of irrigation can be enhanced remarkably by providing supplementary irrigation through these wells, when the canal water is not available.

In the case of well-irrigated areas, providing good quality power supply is the key to farmers securing good control over water delivery to their crops, thereby securing higher returns per unit of land and water. The comparative analysis of water productivity in diesel-pump irrigated farms and electric-pump irrigated farms, where in the case of the former, there is a higher return per unit of land and water (Singh and Kumar 2008; Kumar et al. 2008), are testimony to this.

References

Allen, R. G.; Willardson, L. S.; Frederiksen, H. 1998. *Water Use Definitions and Their Use for Assessing the Impacts of Water Conservation.* Proceedings ICID Workshop on Sustainable Irrigation in Areas of Water Scarcity and Drought, eds. J. M. de Jager, L.P. Vermes, R. Rageb. Oxford, England, September 11-12, pp 72-82.

Amarasinghe, U. A.; Shah, T.; Turral, H.; Anand, B. 2007. *India's water futures to 2025-2050: Business as usual scenario and deviations.* IWMI Research Report 123. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Azzali, S.; Menenti, M. 1987. *Irrigation Water Management in Two Italian Irrigation Districts.* Proceedings Workshop on Earthnet Pilot Project on Landsat-TM Applications, Dec. 1987, Frascati, Italy: 41-48.

Barker, R.; Dawe, D.; Inocencio, A. 2003. Economics of Water Productivity in Managing Water for Agriculture. In. *Water productivity in agriculture: Limits and opportunities for improvement,* eds. J.W. Kijne, R. Barker, D. Molden. Comprehensive Assessment of Water Management in Agriculture Series 1. Wallingford, UK: CABI; Colombo, Sri Lanka: International Water Management Institute (IWMI).

Bastiaanssen, W. G. M. 1998. *Remote sensing in water resources management: The state of the art.* Colombo, Sri Lanka: IWMI, 118p

Bastiaanssen, W.G.M.; Bos, M. G. 1999. Irrigation Performance Indicators using Remotely Sensed Data: A Review of Literature. *Irrigation and Drainage* 13 (4): 291-311.

Chakravorty, U.; Umetsu, C. 2003. Basin-wide water management: A spatial model, *Journal of Environmental Economics and Management*, 45 (2003): 1-23.

Hira, G. S.; Khera, K. L. 2000. Water Resource Management in Punjab under Rice-Wheat Production System, Department of Soils, Punjab Agricultural University, Ludhiana.

[5] A 'chak' refers to the area commanded by a minor, which is the canal off-taking from a distributory of an irrigation system.

Hussain, I.; Sakthivadivel, R.; Amarasinghe, U.; Mudasser, M.; Molden, D. 2003. *Land and water productivity of wheat in the western Indo-Gangetic plains of India and Pakistan: A comparative analysis.* IWMI Research Report 65. Colombo, Sri Lanka: International Water Management Institute (IWMI).

IRMA (Institute of Rural Management Anand) /UNICEF. 2001. White Paper on Water in Gujarat. Report submitted to the Government of Gujarat, Gandhinagar.

Kijne, J.; Barker, R.; Molden, D. 2003. Improving Water Productivity in Agriculture: Editors' Overview. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, eds. J. Kijne, R. Barker and D. Molden. Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Kumar, M. D.; Patel, P.J. 1995. Depleting Buffer and Farmers Response: Study of Villages in Kheralu, Mehsana, Gujarat. In. *Electricity Prices: A Tool for Groundwater Management in India,* ed. M. Moench. Monograph, Ahmedabad: VIKSAT-Natural Heritage Institute.

Kumar, M. D.; Singh, O. P. 2001. Market Instruments for Demand Management in the Face of Growing Scarcity and Overuse of Water in India. *Water Policy* 5 (3): 86-102.

Kumar, M. D.; Singh, O.P.; Samad, M.; Turral, H.; Purohit, C. 2008. *Water Productivity of Irrigated Agriculture in India: Potential Areas for Improvement.* Proceedings of the 7th IWMI-Tata Annual Partners' Meet of IWMI-Tata Water Policy Research Program, 'Managing Water in the Face of Growing Scarcity, Inequity and Declining Returns: Exploring Fresh Approaches', International Water Management Institute, South Asia Regional Office, ICRISAT Campus, April 2-4, 2008.

Meinzen-Dick, R. 1995. Timeliness of Irrigation: Performance Indicators and Impact on Agricultural Production in Sone Irrigation System, Bihar. *Irrigation and Drainage Systems* 9: 371-387, 1995.

Menenti, M.; Visser, T. N. M.; Morabito, J. A.; Drovandi, A. 1989. Appraisal of Irrigation Performance with Satellite Data and Geo-referenced Information. In. *Irrigation: Theory and Practice,* eds. J. R. Rydzewski and C. F. Ward. Proceedings of the International Conference, Institute of Irrigation Studies, Southampton, September 2-15, 1989. 785-801, Pentech Press, London.

Moran, M. S. 1994. Irrigation Management in Arizona using Satellites and Airplanes. *Irrigation Science* 15: 35-44.

Perry, C.J.; Narayanamurthy, S. G. 1998. *Farmers response to rationed and uncertain irrigation supplies.* IWMI Research Report 52. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Perry, C. J. 2005. Irrigation Reliability and the Productivity of Water: A Proposed Methodology Using Evapotranspiration Mapping. *Irrigation and Drainage Systems* 19 (3-4): 211-221.

Roerink, G. J.; Bastiaanssen, W.G.M.; Chambouleyron, J.; Menenti, M. 1997. Relating Crop Water Consumption to Irrigation Water Supply by Remote Sensing. *Water Resources Management* 11 (6): 445-465.

Sarwar, A.; Perry, C.J. 2002. Increasing Water Productivity through Deficit Irrigation: Evidence from the Indus Plains of Pakistan. *Irrigation and Drainage* 51 (1): 87-92.

Seckler, D.; Molden, D.J.; Sakthivadivel, R. 2003. The Concept of Efficiency in Water Resources Management, In *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, eds. J. Kijne, R. Barker and D. Molden. Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Singh, O. P.; Kumar, M.D. 2008. *Using Energy Pricing as a Tool for Efficient, Equitable and Sustainable Use of Groundwater for Irrigation: Evidence from three Locations of India,* presented at the 7th Annual Partners' Meet of IWMI-Tata Water Policy Research Program, International Water Management Institute, South Asia Regional Office, ICRISAT Campus, HyderabadApril , 2-4, 2008.

Svendson, M.; Small, L. 1990. Farmer's Perspective on Irrigation Performance. *Irrigation and Drainage Systems* 4 (4): 385-402.

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