Water Productivity of Irrigated Agriculture in India: Potential Areas for Improvement

[1]M. Dinesh Kumar, [2]O.P. Singh, [3]Madar Samad, [4]Chaitali Purohit and [4]Malkit Singh Didyala
[1]IWMI-TATA Water Policy Program, Hyderabad, India
[2]Department of Agricultural Economics, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi.
[3]India Program, International Water Management Institute, Hyderabad, India
[4]IWMI-TATA Policy Program

Introduction

Economic value of water in agriculture is much lower than that in other sectors (Barker et al. 2003), including manufacturing (Xie et al. 1993). Growing physical shortage of water on the one hand, and scarcity of economically accessible water owing to increasing cost of production and supply of the resource on the other had preoccupied researchers with the fundamental question of increasing the productivity of water use in agriculture in order to get maximum production or value from every unit of water used (Kijne et al. 2003). Raising water productivity is the cornerstone of any demand management strategy (Molden et al. 2001).

Raising crop water productivity means raising crop yields per unit of water consumed, though with declining crop yield growth globally, the attention has shifted to potential offered by improved management of water resources (Kijne et al. 2003). It is necessary to ease water scarcity and to leave more water for other human uses and nature, if we want to reduce the negative consequences of reallocating water to other sectors. But the key to understanding the ways to enhance water productivity is to understand what it means (Kijne et al. 2003). After Molden et al. 2003, the definition of water productivity is scale dependent. Water productivity can be analyzed at the plant level, field level, farm level, system level and basin level, and its value would change with the changing scale of analysis. Many researchers have argued that the scope for improving water productivity through water management, or efficiency improvement, is often over-estimated and the reuse of water is under-estimated (Seckler et al. 2003).

The classical concept of irrigation efficiency used by water engineers omitted economic values and looked at the actual evapotranspiration (ET) against the total water diverted for crop production (Kijne et al. 2003). Moreover, it does not factor in the ‘scale effect’ (Keller et al. 1996). With a greater opportunity to manipulate crop yields without altering consumptive use (ET) and growing cost of production and supply of water, with increased cost of water control to achieve higher physical efficiency in water use, and with growing pressure to divert the water to alternative uses, there have been major advancements in the theoretical discourse on ways to analyze water productivity in crop production. This seems to have led to more comprehensive definitions of water productivity.

Analyzing crop water productivity involves complex considerations and there is no single parameter which could determine the efficiency with which water is used in crop production. The major crop water productivity parameters used in literature are physical productivity of water expressed in kilograms of crop per cubic meter of water diverted or depleted (kg/m^3); net or gross present value of the crop produced per cubic meter of water (Rs/m^3) known either as combined physical and economic productivity of water use or water productivity in economic terms; and net or gross present value of the crop produced against the value of the water diverted or depleted (Kijne et al. 2003).

Although crop production is the major consumptive use of water in many river basins, increasingly there are other competing uses of water, usually with higher returns per unit of water depleted. Therefore, changing inter-sectoral water allocation norms in favor of more efficient uses would result in higher overall basin water productivity, although it is important that existing users are properly compensated. Also, at the level of river basin, opportunities might exist for enhancing crop water productivity by growing certain water-intensive crops in regions where water productivity is greater due to more favorable climatic and agronomic factors (Abdulleev and Molden 2004), indicating the need for inter-regional water allocation.

On the other hand, enhancing water productivity at the field or irrigation system level through water control may adversely affect the availability of water for downstream uses in a closed basin. The reason is the probable reduction in the non-consumptive part of the water applied, along with the reduction in non-beneficial part of the depleted water that can occur due to water control measures. If those downstream uses have a higher return per unit of water use, water control measures would result in productivity losses. Also, at the basin level, regional food security and employment needs would be other important considerations besides maximizing water productivity in crop production. Size of the market would be another consideration for making choices for large-scale shift to high-valued crops that give higher return per unit of depleted water, at the basin scale. Hence, considerations for enhancing basin level water productivity would be different from that for maximizing the farm level and system level water productivity.

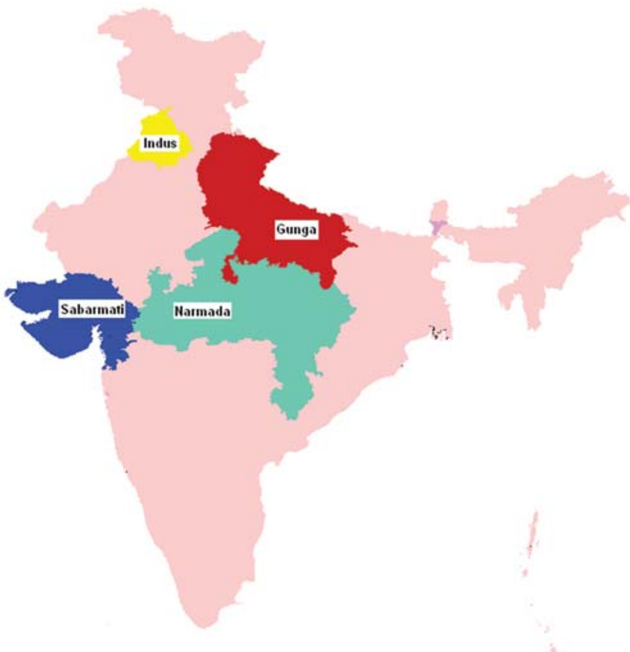
In a nutshell, if one integrates the 'scale consideration' and various physical and economic considerations in assessing water productivity, there could be many opportunities and constraints in enhancing water productivity in crop production. The opportunities could come from yield improvements through better agronomic inputs and obtaining greater water control to reduce the 'depleted water'; diverting the available water to crops that give higher cash return per unit volume of water consumed; growing crops in areas where their ET values are lower; and reducing the amount of applied water which has high opportunity costs whereas the constraints could come from the regional food and employment security concerns, and potential decline in market value of the high-valued crops in the face of surplus production.

Great opportunities exist for enhancing the productivity of water use in agriculture in India. Some of them include: 1) rationing water allocation to ensure meeting the evapotranspirative needs of the plants at the critical stages, which means establishing greater control over timing and the quantum of water delivery; 2) providing appropriate quantum of fertilizer and nutrient inputs to the crops to realize the yield potential; and growing certain crops in regions where the ET requirements are lower and genetic potential of the crop could be realized. What needs to be understood is that while the yield would increase with an increase in actual ET, the water productivity would start leveling off and then start declining much before the yield reaches the maximum (Molden et al. 2003). This means there is a clear trade-off between yield enhancement and water productivity enhancement at higher levels of ET. When water becomes scarce, the irrigation water allocation has to be optimized to get positive marginal productivity.

Objectives, Approach and Methodology

In this study, the scope for water productivity enhancement is analyzed by estimating 1) the incremental changes in irrigation water productivity, and marginal productivity of irrigation water for select crops with increase in irrigation water allocation and fertilizer inputs; 2) the spatial variation in average productivity of crops vis-à-vis agro-climatic regions; and 3) comparative average water productivity with different sources of irrigation which represent different degrees of control over water delivery.

Map 1. Map Showing Study Locations.



The locations and regions in which the study basins are located are shown in shared form in Map 1. The approach used in the study is a case study based using primary surveys. Four river basins in India were selected for the study. They are Indus Basin; Narmada River basin; Ganges Basin and Sabarmati River basin.

The study analyzed water productivity variations across 1) farms within the same type of crops and with the same pattern of irrigation; and 2) irrigation types from wells, canals and conjunctive use; and 3) agro-climates within the same basin. It involved collection of data on parameters governing water productivity in crop production such as cropping system, cropped area, crop inputs (bio and chemical fertilizers, farm labour, irrigation water use, irrigation schedules, and crop technology), crop outputs (main product, by product, market price of crops), and method of irrigation. For each irrigated crop, the sample size is 30-35 for each agro-climate within a river basin. In addition to that, there were samples for each type of irrigation source. Hence, the maximum sample size was 90 in the one location; but limited to only situations where sufficient samples for different modes of irrigation were available.

Data and Sources

Data used for water productivity analysis are primary data from farmers. Data collection was done using a structured questionnaire from locations in all the four basins, viz., Indus, Ganges, Narmada and Sabarmati. From the Indus, only one location was covered; from Ganges also one location was covered; from Narmada, nine locations, each representing one agro-climatic condition, was covered. From Sabarmati, four locations, each representing one agro-climate, were selected. The data collected from farmers included data on crop inputs comprising cost of seeds, labor, fertilizer and pesticides, quantum of irrigation water, and quantity (weight in kg) and market price (Rs/kg) of main and byproducts of the crop output. In addition, the discharge of irrigation wells (liter/sec) was measured using a bucket and stop watch to quantify the volume of water pumped, for which data on number and hours of irrigation concerning each crop and for each season were obtained from the farmers.

Analytical Procedure

The physical water productivity $\sigma_{irri,\,i}$(kg/m^3) and water productivity in economic terms, $\theta_{irri,\,i}$(Rs/m^3) in a purely irrigated crop i are estimated as:

$$\sigma_{irri,\,i} = \frac{\nabla_{irri,\,i}}{1{,}000\Delta_{irri\,,i\,i}}\,;\quad \theta_{irri,\,i} = \frac{NR_{irri,\,i}}{1{,}000\Delta_{irri\,,i\,i}} \quad \text{.................1, 2,}$$

$\Delta_{irri\,,i}$, and $\nabla_{irri\,,i}$ are the irrigation water dosage (mm) and yield (kg/ha) for purely irrigated crop$_i$, respectively in mm. $NR_{irri,\,i}$ is the net return per unit area of the crop (Rs/ha). All winter crops selected for the study are treated as purely irrigated crops, and the green water use for these crops was ignored. The reason is that their yields under un-irrigated condition as well as residual soil moisture before sowing are negligible. All crops covering two seasons, viz., *kharif* and winter, having no rain-fed yields were also treated as irrigated crops. Winter wheat in Narmada Basin, cotton in West Nimar in the Narmada Basin, winter wheat in Uttar Pradesh (UP), Punjab, and all crops selected from Sabarmati basin (namely, wheat, castor, bajra and cotton) were treated as irrigated crops and, therefore, the water productivity values estimated for them are irrigation water productivity[1].

---

[1] In areas with moderate rainfall like eastern UP, this must have resulted in over-estimation of irrigation water productivity.

Marginal physical productivity of water, $\sigma_{comb\text{-}irri,\, j}$(kg/m^3), and marginal water productivity in economic terms $\theta_{comb\text{-}irri,\, j}$(Rs/m^3) for crops, which receive supplementary irrigation, and having rain-fed yields, with respect to irrigation, are estimated as:

$$\sigma_{comb\text{-}irri,\, j} = \frac{\nabla_{comb\text{-}irri,\, j}}{1{,}000\Delta_{comb,j}}\ ;\ \theta_{comb\text{-}irri,\, j} = \frac{NR_{comb\text{-}irri,\, j}}{1{,}000\Delta_{comb,j}} \text{ ....3, 4,}$$

Where, $\nabla_{comb\text{-}irri,\, j}$ is the yield corresponding to irrigation water applied (kg) and $\Delta_{comb,j}$ is the irrigation water applied for the crop *j* (mm). $NR_{comb\text{-}irri,\, j}$ is the net return per unit area corresponding to the irrigation water applied for the same crop (Rs/ha). $\sigma_{comb\text{-}irri,\, j}$ and $\theta_{comb\text{-}irri,\, j}$ were obtained by running a regression of yield and net returns from the crop against irrigation water applied for each crop, respectively. The regression coefficients give the marginal physical productivity of water and water productivity in economic terms, respectively, of irrigation for these crops. This gives the mean value of marginal water productivity for all the farmers growing that crop. One major assumption involved in this analysis is that the water application is still in the scarcity regime, meaning the total consumptive use may fall short of or just meet the evapotranspirative demands. Therefore, the response curve of yield and net return to irrigation water use were treated as linear. This no way means that the volumetric water applied (effective rainfall and irrigation) is below ET demand, as farmers can provide excessive irrigation in certain periods of the crop season, resulting in losses.

The marginal water productivity of irrigation water for individual farmers were estimated by subtracting the ‘a’ coefficient , i.e., Y intercept, of the regression equation for yield and net return, respectively, from their corresponding crop yield and net returns, and dividing by the volume of irrigation water applied. Paddy from Jabalpur and Mandla in Narmada River basin was considered for this methodology, as it had rain-fed yield in many locations.

The drivers of change in water productivity were analyzed by running regressions of crop yield (dependent variable) against irrigation dosage and fertilizer dosage (as separate independent variables) for select crops (viz., wheat and cotton); and crop water productivity in economic terms against fertilizer dosage and irrigation water dosage for the same crops.

Field Level Water Productivity: Results from Four Indian River Basins

There are several studies done over the past 2 years analyzing water productivity in irrigated production covering many heterogeneous physical settings in India, in terms of agro-climate and overall water resource availability and quality. The locations included part of Indus Basin in south-western Punjab; part of Ganga Basin in eastern Uttar Pradesh; and different locations in Sabarmati River basin in Gujarat. The studies included analyses of the productivity of irrigation water for several crops from both physical and economic point of view. All the analyses are based on well-irrigated crops and the volume of applied water was used in the denominator of water productivity.

The results of the analyses are presented in summary form in Table 1 to Table 2 to highlight the variations in water productivity with the same location across farmers; and across locations within the same basins; and across basins for the same crop. The irrigated crops considered for the analyses are winter wheat (Punjab, UP, Gujarat, and Madhya Pradesh); and *kharif* paddy in Punjab, UP, Gujarat, Madhya Pradesh.

As Table 1 shows, there are major variations in water productivity across farmers within the same location. This is not only restricted to water productivity in economic terms, but also to the physical productivity of water use. For instance, in the case of Batinda in Punjab, the data on water productivity in wheat were analyzed for 80 farmers and the variations are remarkable. The physical productivity of water varies from 1.29 kg/m^3 to 4.27 kg/m^3. The water productivity in economic terms ranges from a lowest of Rs.1.25/m^3 to a highest of Rs.13.35/m^3.

Table 1. Irrigation water productivity in wheat in three river basin locations in India.

Name of the basin	Name of the region	Name of the district	Physical productivity (Kg/m^3)		Water productivity in economic terms (Rs/m^3)	
			Average	Range	Average	Range
Narmada	Central Narmada valley	Hoshangabad	0.91	0.43 – 1.60	2.31	0.034 – 7.48
		Jabalpur	0.47	0.23 – 0.88	1.06	0.022 – 4.66
		Narsingpur	0.53	0.26 – 0.75	1.11	0.006 – 3.52
	Jhabua hills	Jhabua	0.60	0.38 – 0.88	1.20	0.05 – 11.58
	Satpura plateau	Betul	0.84	0.52 – 2.06	2.61	0.10 – 10.21
	Malwal plateau	Dhar	1.05	0.64 – 1.80	2.04	0.072 – 6.67
	Nimar plain	West Nimar	0.83	0.52 – 1.62	1.99	0.012 – 7.60
	NHRCh	Mandla	1.80	0.98 – 2.95	4.09	0.21 – 10.79
	Vindhya plateau	Raisen	1.01	0.61 – 1.58	2.27	0.25 – 7.67
Indus	South-Western	Batinda Punjab	2.33	1.29 – 4.27	5.93	1.25 – 13.35
Ganges	Eastern Uttar	Varanasi Pradesh	2.61	1.65 – 4.98	10.80	5.02 – 24.51
Sabarmati	North Gujarat, Western India	Sabarkantha (Bayad)	2.75		8.9	
		Sabarkantha (Himmatnagar)	0.80		2.3	
		Ahmedabad	0.71		1.1	
		Kheda	1.71		4.88	

Source: Authors' own analysis based on primary data

Note: NHRC: Northern Hill Region of Chhattisgarh

As regards variations in water productivity across regions within the same basin, Narmada is the most illustrative example. Within Madhya Pradesh part of Narmada Basin, wheat is grown in all the seven agro-climatic regions that fall inside the basin, and is a purely irrigated crop in the sense that it is not possible to grow this crop just using the soil moisture available after the rains, irrespective of the high magnitude of monsoon rains available in certain regions. Data on irrigation water productivity were available for as many as 45 farmers from each location. Hence, comparison of water productivity in wheat highlights the potential variation in water

Table 2. Marginal productivity of irrigation water in paddy in three selected river basins in India.

Name of the basin	Name of the region	Name of the district	Physical productivity (Kg/m^3)		Water productivity in Economic terms (Rs/m^3)	
			Average	Range	Average	Range
Narmada	Central Narmada valley	Jabalpur	1.62	0.85 – 2.57	3.95	0.05 – 10.28
	NHR.C	Mandla	2.13	1.20 – 4.00	1.43	0.43 – 7.74
Indus	Punjab	Batinda	3.69	3.17 - 4.36	10.57	4.47 – 24.94
Ganga	UP	Varanasi	2.54	1.21 – 3.96	4.90	0.94 – 11.89
Sabarmati	North Gujarat,	Sabarkantha	0.42		0.91	
	Western India	Ahmedabad	1.06		3.34	
		Kheda	0.92		2.98	

*Source:*Authors' own analysis based on primary data collected from the three basin areas

Note: NHRC: Northern Hill Region of Chhattisgarh

productivity possible for irrigated crops. The average physical productivity of irrigation water in wheat ranges from 0.47 kg/m^3 in Jabalpur to 1.8 kg/m^3 in Mandla.

Also highly significant are the water productivity variations across the four river basins, viz., Indus, Ganges, Narmada and Sabarmati. This could be the result of variations in water availability situation, agro-climate and the level of agricultural development. First of all, Indus is a physically water-scarce river basin; so is Sabarmati, and are all 'closed' basins, wherein all the surface water resources are diverted for various uses within the basin and are fully depleted, and additionally, the groundwater resources in these basins are also fully utilized. Narmada Basin still has unutilized water resources, particularly surface water. Agro-climatically, south western Punjab has arid climate; MP part of Narmada has climatic conditions varying from sub-humid to semi-arid. Finally, the degree of the adoption of crop technologies varies from basin to basin. While Punjab is known for progressive farmers, and a high level of adoption of green revolution technologies and high agricultural productivity, Madhya Pradesh's agriculture is relatively very backward. The adoption of modern farming technologies, including irrigation is quite recent in MP. The average water productivity of wheat ranges from a lowest of 0.47 to a highest of 1.8 kg/m^3 in Narmada Basin to 2.33 kg/m^3 in Batinda, Punjab (Indus) to 2.61 kg/m^3 in Banaras, UP (Ganges).

The variations in physical productivity of water across farmers within one location; across different locations within a basin; and between basins result in a higher degree of variation in the productivity of water use in economic terms as shown in last columns of Table 2. While the ratio of the highest and the lowest values of physical productivity is 3.0 in eastern UP in Ganges, the corresponding ratio for combined physical and economic productivity is 4.8 for the same location. While the ratio of the highest and the lowest values of physical productivity of irrigation water in wheat is 3.25 in south-western Punjab in the Indus, the corresponding value for water productivity in economic terms for the same location is 12.6. The ratio of average physical productivity of irrigation water in wheat across basins is 1.45 (3.69/2.54) and when south western Punjab and eastern UP are compared, the corresponding ratio for combined physical and economic productivity is 2.15 (10.57/4.90).

Determinants of Water Productivity Variations

Increasing of fertilizers and nutrients increases the crop yields up to a point but the physical productivity of water can be manipulated without any change in irrigation inputs. With the same amount of water applied, the crop consumptive use would change depending on the timing of water. Optimum water application can ensure full utilization of the applied water for evapotranspirative demand. Non-availability of moisture at critical stages of crop growth can significantly reduce the crop growth and yield and the reduction would not be proportional to the reduction in water applied or water consumed. Therefore, the quality of irrigation (reliability and adequacy) should affect water productivity, with the same amount of irrigation water applied. However, against this, plants have highly developed adaptive mechanisms to compensate for water stress in different growth stages, and the only way to factor these in properly is to use a well calibrated crop growth model, or through the development of crop production functions. Similarly, the same crop would have different water requirements under different climates and, therefore, different water productivity levels with the key inputs such as fertilizers, labor and irrigation remaining the same.

While labor and fertilizers and nutrient inputs can help enhance the crop yield and physical productivity of water, the economic productivity could decrease, as the marginal increase in yield and gross return may not keep pace with the marginal increase in input costs to achieve such high levels of yield beyond a point (Barker et al. 2003). Hence, water productivity in economic terms is important for assessing the efficiency with which water is used in crop production.

Water productivity can also be enhanced by reducing the amount of non-beneficial depletion of applied water in the field, through water control. Water control is to enable the supply of water close to the difference between crop water requirement, and available soil moisture in the root zone. The measures for this include on-farm water management practices, improving the conveyance of water. Micro-irrigation systems take care of water control for many crops, and in certain other crops by farm leveling. We would demonstrate the impact of these factors on changing the key determinants of water productivity and water productivity as such.

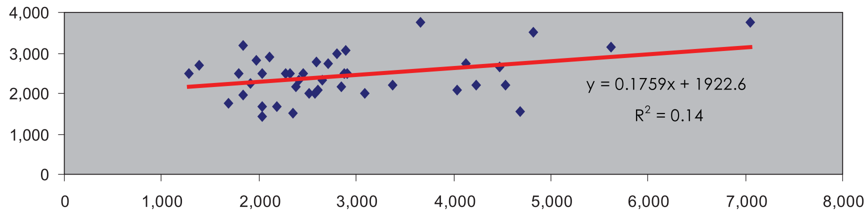
Identifying the Causes of Productivity Variations Across Farmers

In order to analyze the variations in yield and water productivity across farmers, the data collected from four agro-climatic regions in Narmada River basin were analyzed. The analysis included the following: 1) the crop yield response to irrigation water applied; 2) the water productivity (Rs/m^3 of water applied) response to irrigation; 3) the yield response to fertilizer use; and 4) the water productivity response to fertilizer application.

Responses of Yield and Water Productivity to Applied Water

In the case of Hoshangabad District, data of applied water, fertilizer dosage, crop yield, and water productivity in economic terms (estimated) were available for two consecutive years, viz., 2002 and 2003. The regression analysis showed that the relationship between the dosage of irrigation water and yield for winter wheat of 2002 is linear. The R square value here is only 0.14, and hence the relationship is not strong. As shown in Figure 1, wheat yield responded to increase in the dosage of irrigation water and for the same level of irrigation, the yield

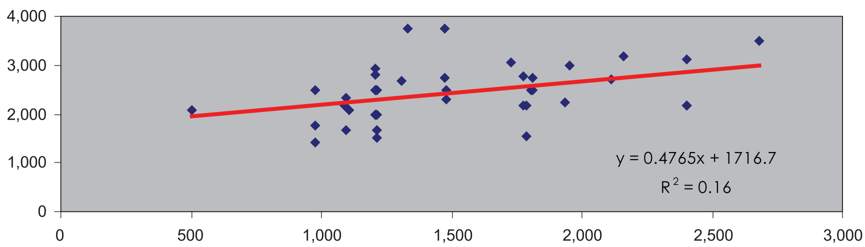
Figure 1. Yield vs. irrigation dosage in wheat in Hoshangabad in 2002.



differences across farmers are quite substantial. This can perhaps be explained by the differential levels of fertilizer use by these farmers, differences in soil quality, changes in date of sowing, and differences in crop variety.

Figure 2 shows the graphical representation of the variation in yield with differential levels of fertilizer input. It shows a slightly stronger relationship between fertilizer use and crop yield (R^2=0.16). Higher dosage of fertilizer meant higher wheat yield. But, this does not mean that it is the higher fertilizer dosage which causes higher yield. Generally, it is the farmers who have good irrigation facilities and use a higher quantum of irrigation water who use a proportionally higher dose of fertilizers. Due to this co-linearity between irrigation and fertilizer dosage, the increase in yield cannot be attributed to higher dosage of fertilizers. Hence, in order to segregate the effect of fertilizer dose on crop yield, a more thorough examination of data was carried out.

Figure 2. Yield vs. fertilizer dosage in Hoshangabad in 2002.

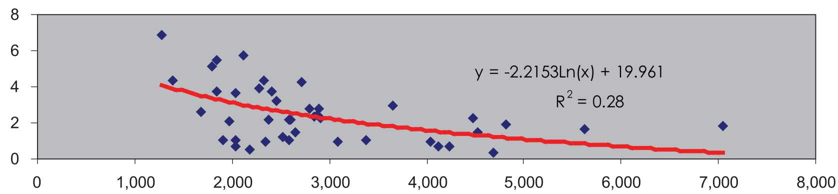


It was found that two farmers applying the same dosage of irrigation (1,834 mm) applied different quantities of fertilizers (worth Rs.1,213/ha and Rs.2,160/ha, respectively) and got different levels of yield (19.8 quintals/ha and 31.7 quintals/ha, respectively). In another case, two farmers applied the same dosage of irrigation (2,035mm), but applied fertilizers in varying doses (worth Rs.975/ha and Rs.1,205/ha respectively), and got different yields (1,480 kg/ha and 2,500 kg/ha respectively).

Figure 1 also meant that many of the farmers are applying scarcity irrigation and could have actually got higher yield had they applied higher dozes of irrigation with proportional increase in fertilizer inputs. But, the amount of water applied to the soil also influences the nutrient absorption capacity of the plants and, therefore, irrigation water shortage might be limiting farmers' ability to apply adequate quantities of fertilizers. By and large, the maximum yield corresponded to maximum irrigation.

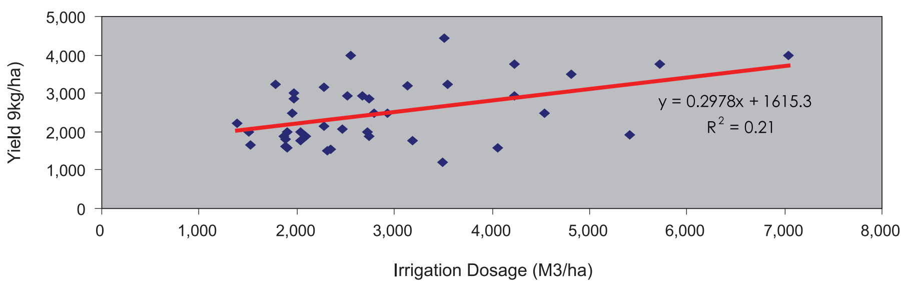
The graphical representation of water productivity response to irrigation is given in Figure 3. The relationship is inverse and exponential. Higher dosage of water applied meant lower water productivity (R^2= 0.28). Generally, those who applied higher dosage of water had lower levels of water productivity, while many farmers who applied lower dosage of irrigation (200 to 225 mm of irrigation) got high water productivity. At the same time, many farmers who maintained similar dosage of irrigation got much lower water productivity (Rs/ m^3), which could be due to the low levels of fertilizer inputs, which reduced the crop yields significantly. The lower water productivity at high dosage of irrigation could be due to lack of proportional increase in yield, increase in cost of fertilizers which reduces the net returns, and increase in volume of water applied, which increases the value of denominator.

Figure 3. Water productivity vs. irrigation dosage in wheat in Hoshangabad in 2002.



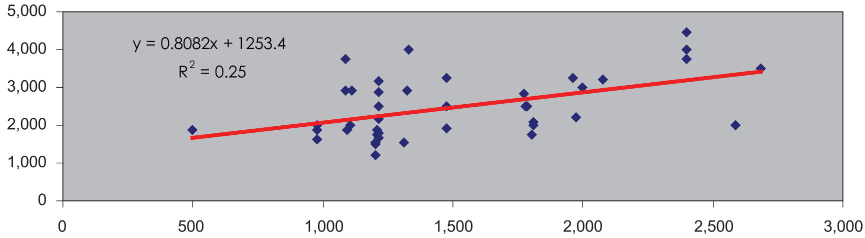
The analysis was repeated for the year 2003. It showed a stronger positive linear relationship between applied water and crop yield in wheat (R^2=0.21). Higher levels of water dosage generally ensured higher yield (Figure 4). The incremental yield due to increase in dosage of irrigation water by 100 mm was around 230 kg/ha. But, there were significant yield differences between farmers who applied more or less the same amount of water. This could be explained by the factors mentioned above. Nevertheless, slightly improved relationship better fertilizer and irrigation dosage (with an R square value of 0.25) confirms this (Figure 5).

Figure 4. Yield vs. irrigation in wheat in Hoshangabad in 2003.



The regression values for the response of yield to irrigation dosage being very small (Figure 1 and Figure 4), one could argue that many factors other than irrigation explain yield variations. But, given the fact that the data that are being presented here are for different farmers, who represent different soil conditions, different planting dates and different seed

Figure 5. Yield vs. fertilizer dosage in wheat in Hoshangabad in 2003.

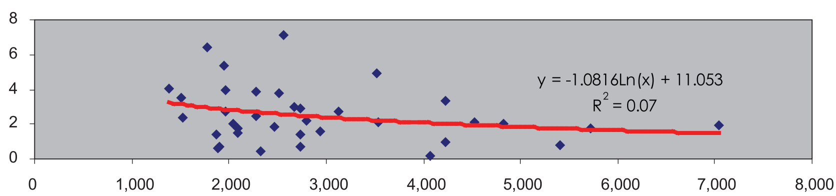


varieties, all of which having a potential to influence the crop yield, the relationship and regression coefficient is significant[2]. Also, the slope of the yield curve is very mild in the case of Figure 3, which is quite contrary to what can normally be found given the wide range in irrigation water dosage among the sample farmers.

The regression between water dosage and water productivity (Rs/m^3) showed a poor inverse relationship between the two unlike what was found for 2002 (Figure 6). This could be due to the reasons explained above for the same crop grown during 2002. Some of the farmers who were in the lower range of irrigation dosage (between 200 mm and 300mm) got very low water productivity values (between Rs.0.41/m^3 and Rs.1.38/m^3), whereas some other farmers got values of approximately Rs.7/m^3 of water. This could be due to the wide differences in fertilizer dosage, which resulted in differential yields. The strong linear relationship between fertilizer dosage and crop yield (R^2=0.25) as shown by Figure 5 is a testimony to this.

A closer look at the chart showing relationship between irrigation dosage and crop yield also provides better clues to this effect. There are many examples of farmers applying more or less the same dosage of irrigation, but applying different dosage of fertilizers and getting different levels of yield. For instance, two farmers who applied irrigation dosages of 2,518 and 2,557 m^3 of water to their wheat, applied different levels of fertilizers (worth Rs.1,112/ha and Rs. 2,400/ha) and in turn got yields of 2,910 kg/ha and 4,000 kg/ha, respectively.

Figure 6. Water productivity vs. irrigation dosage in wheat in Hoshanganad in 2003.



[2] With changing soils, the nutrient levels could change. With changing planting dates, the soil moisture availability could change; so the crop water requirement and yield potential. Yield potential could also change with seed variety.

The analysis was repeated for another region, west Nimar in Narmada Basin, for cotton in 2003. After the rainy season, the crop is normally irrigated. The yield response to irrigation was polynomial (Figure 7), with yield increasing up to a point (from 100 mm to 300 mm), and then declining. Many farmers who applied close to 300 mm got the highest yields. Beyond 300 mm, the yield started declining. The curve showing the water productivity (Rs/m^3) response of irrigation dosage (Figure 8) is again 'polynomial'. With increase in dosage of irrigation, while the yield increased, the water productivity did not get affected much. But, beyond the point where the yield was optimum, increase in irrigation dosage led to declining water productivity. This is the third set of response curves.

Figure 7. Yield vs. irrigation water dosage in cotton in West Nimar in 2003.

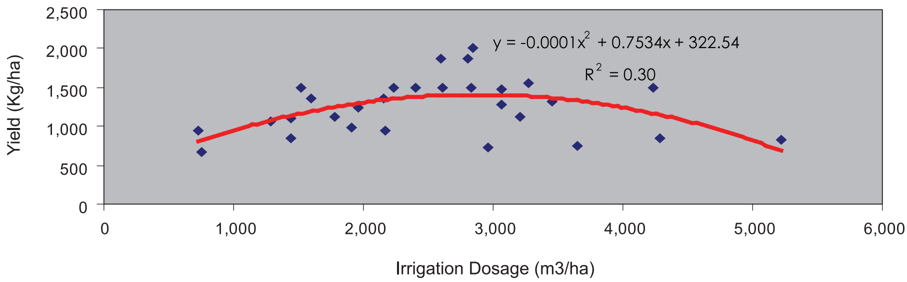
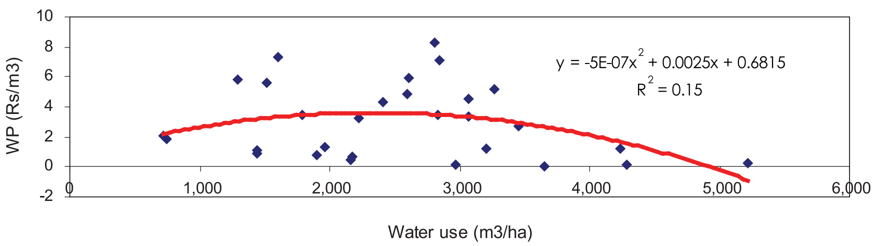


Figure 8. Water use vs. water productivity in cotton in West Nimar in 2003.



Yield and Water Productivity Response to Fertilizer Dosage

As regards yield response to fertilizer inputs, in the case of wheat in Hoshangabad, it was found that the response is extremely weak for the drought year (2002) as shown in Figure 2 (R^2=0.16). At the same time, the response was reasonably good for the normal year 2003 (R^2 =0.25) as shown in Figure 5. Water productivity was also higher for farmers who applied higher dosage of fertilizers (R^2=0.27) during the season of 2003, though such trends were not seen for the drought year of 2002. Such a response does indicate that the farmers are optimally using fertilizers and irrigation water to enhance the returns.

In the case of cotton in West Nimar, water productivity response curve for fertilizer dosage was found to be 'polynomial' for the drought year (2002), with productivity (Rs/m^3) increasing from the lowest values at low levels of fertilizer use towards the middle range, and then declining (R^2= 0.11). Such a response curve could be explained as resulting from very high doses of fertilizers generally accompanied by an increased dose of irrigation water. Higher dosage of irrigation water could also increase the chances of fertilizer leaching, reducing the nutrient intake by the plants and flattening the response curve of yield. At the same time, the yield gains obtained due to the same were not significant enough to offset the effect of increased cost of inputs, and increase in the volume of water applied. This is quite natural as the farmers are interested in maximizing the returns per unit of land, and not water.

Analyzing the Changes in Water Productivity Due to Changes in Quality and Reliability of Irrigation

There is not much empirical evidence available from across the country to provide evidence to the effect that greater reliability of irrigation water supplies and control over water allocation leads to greater water productivity.

Analysis from groundwater irrigated areas of North Gujarat showed that the gross returns per cubic meter of applied water were higher for shareholders of tubewell companies, when compared with that of farmers who were buying water from well owners. The gross water productivity was Rs. 5.61/m^3, as against Rs.4.61/m^3 for water buyers. The gross returns only indicate the physical efficiency of water use, as it does not take into account the input costs, and only converts the main product and by-product into cash equivalents. The difference between the two is in the 'terms of irrigation services'. In the case of shareholders, the entitlement of water is fixed in volumetric terms, and water supply is highly reliable. In the case of water buyers, the well owner supplies enough water to make sure that the cultivator gets sufficient yield as his irrigation charge is paid in proportion to the total crop yield.

The difference between the two cases is in terms of water allocation norms and the reliability of water supply. In the case of shareholders, supply is rationed and known to the farmers much in advance of the season. Hence, they are able to do proper water budgeting and apply optimum dosage of fertilizers whereas the farmers who purchase water on hourly basis are at the mercy of the well owners. They do not try to optimize fertilizer dosage, and go for the best quality seeds, as they are not sure of getting adequate water supplies. This reinforces the fact that net return from crop production is less elastic to the cost of irrigation than the reliability of irrigation.

Yields in two major crops, viz., wheat and paddy in three different types of irrigation systems, which represent three different degrees of water control, in two different regions of Bist Doab area in Punjab were compared to understand the impact of differential quality of irrigation water. The three systems selected are canal irrigation, well irrigation and conjunctive use. The underlying premise in the analysis is that farmers using canal water do not have complete control over irrigation and, hence, will not be able to apply water at critical stages in right quantities. On the other hand, farmers using well water, despite incurring higher costs in terms of capital, would be able to apply water to their crops as and when they require, subject to the availability of electricity. As farmers using both canal water and well water should have a higher degree of control over water application compared with that of canal irrigators, the 'overall quality of irrigation' would depend on what proportion of the total demand is met from canals, and what proportion is met from groundwater.

But, analysis involved comparing water productivity in wheat under different sources of irrigation in two distinct agro-ecological regions. This was because an adequate number of irrigators for each of the three sources of irrigation was not available from the same agro-ecological region. The first is lower Bist Doab area, with low rainfall and semi-arid climate; and the second, the sub-mountainous region with medium to high rainfall with sub-humid climate. Comparison of yield with different sources of irrigation could be made between conjunctive use and canal water (in sub-mountainous region). The analysis showed that yield figures are the lowest for farmers using only canal water for both paddy and wheat, and the second lowest for farmers using both canal water and groundwater (Table 3). The farmers using well water (in Jalandhar and Kapurthala) were found to be getting the highest yield. The yield differences are quite substantial between categories within the region and across regions. While agro-ecology would be an important factor affecting the crop yields, such large differences in yield could only be explained by the quality and reliability of irrigation water.

Table 3. Differential land productivity with varying quality of irrigation in Punjab.

Name of region	Name of district	Predominant source of irrigation	Crop yield (ton/ha)	
			Paddy	Wheat
Lower Bist Doab	Jalandhar	Well water	6.26	4.68
			5.20	4.40
	Kapurthala	Well water	5.98	4.73
			5.52	5.30
Sub Mountainous	Hoshiarpur	Conjunctive use	4.46	3.82
			4.65	3.79
		Canal water	2.77	3.52
			3.47	2.80

Source: Authors' own analysis using primary data

Analyzing Water Productivity Variations across Regions Due to Climatic Advantages

Spatial analysis of water productivity of selected crops carried out for nine districts in seven agro-climatic regions in Narmada Basin are presented in Table 4. The spatial analysis of water productivity is an important aspect of the strategy to enhance water productivity at the agro-climatic level (Kijne et al. 2002), as productivity of applied water is a function of agro-climate. Both physical productivity and water productivity in economic terms is determined by the climatic conditions, which determines the actual consumptive water requirements, and the availability of soil moisture from precipitation. In regions, with favourable climatic conditions, the biomass output per unit of water evapotranspired would be higher as in regions with less favorable climate. Here, we have compared water productivity of wheat and paddy which are two significant crops.

The physical productivity of applied water for grain production during the normal year was estimated to be the highest for northern hill region of Chhattisgarh in Mandla District (1.80 kg/m^3) although Raisen District in the traditional wheat-growing belt and it was the lowest for Jabalpur in Central Narmada Valley (0.47 kg/m^3). This is mainly due to the major difference in irrigation water applied, which is 127 mm against 640 mm for Jabalpur. This is a significant difference, with the highest being 250 % more than the lowest. The difference in irrigation can be attributed to the difference in climate between Jabalpur (dry semi-humid) and Mandla (moist sub-humid), which changes the crop water demand. It can also be noted that the physical productivity in the normal year is the second highest in Raisen (1.01 kg/m^3). Higher biomass output per unit volume of water (physical productivity) should also result in higher economic output especially when the difference is mainly due to the climatic factors, which change the ET requirements, unless the factors which determine the cost of inputs significantly differ. In our case, it was found that the net economic return per cubic meter of water was the highest for the same region for which physical productivity was higher (Rs. 4.09/m^3), followed by Raisen (Rs. 2.77/m^3). But the same was the lowest for Narsingpur (Rs. 0.86/m^3), which had the second lowest physical productivity.

The difference between gross and net water productivity (furnished in Table 4) is that in the first one, the total economic value of outputs from unit area of outputs is only considered in the numerator, whereas in the second case, the net income from crop production after deducting the cost of inputs per unit area is considered.

Table 4. Region-wise irrigation water productivity (wheat) and marginal productivity of irrigation water (paddy) in Narmada River basin for selected crops.

Name of the region	Name of the district	2002-03 (Drought year)				2003-04 (Normal year)			
		Physical productivity (Kg/m^3)		Water productivity in economic terms (Rs/m^3)		Physical productivity (Kg/m^3)		Water productivity in economic terms (Rs/m^3)	
		Main product	By-product	Gross	Net	Main product	By-product	Gross	Net
Wheat									
1. Central Narmada Valley	Hoshangabad	0.81	0.81	5.74	2.09	0.91	0.90	6.25	2.31
	Jabalpur	0.44	0.43	3.08	0.89	0.47	0.46	3.42	1.06
	Narsingpur	0.53	0.49	3.84	1.11	0.49	0.47	3.47	0.86
2. Jhabua Hills	Jhabua	0.73	0.65	5.32	1.38	0.60	0.55	4.69	1.20
3. Satpura Plateau	Betul	0.72	073	5.34	2.14	0.84	0.82	6.05	2.61
4. Malwal Plateau	Dhar	1.07	1.02	8.05	2.46	1.05	1.05	7.67	2.04
5. Nimar Plain	West Nimar	0.85	0.83	6.65	2.38	0.83	0.83	6.20	1.99
6. NHRC	Mandla	0.92	0.88	6.62	1.44	1.80	1.78	12.75	4.09
7. Vindhya Plateau	Raisen	0.77	0.77	5.33	2.00	1.01	1.01	6.82	2.77
Paddy									
1. Central Narmada Valley	Jabalpur	1.08	0.79	5.86	1.99	1.62	1.15	9.36	3.95
2. NHRC	Mandla	1.74	1.26	11.69	2.12	2.13	1.59	12.50	1.43

Source: Authors' own analysis based on primary data

Note: NHRC: Northern Hill Region of Chhattisgarh

As regards paddy, there are only two regions which irrigate paddy. The physical productivity for grain during the normal year was estimated to be higher for northern hill region of Chhattisgarh in Mandla District (2.13 kg/m^3) whereas it was only 1.62 kg/m^3 in Jabalpur District of Central Narmada Valley. Likewise, water productivity in economic terms was found to be higher for northern hill region of Chhattisgarh (Rs.3.95/m^3) as against Rs.1.43/m^3 for Jabalpur in Central Narmada Valley. Similar figures were found for the drought year (2002) in which the physical productivity of applied water was 1.74 kg/m^3 in Mandla against 1.08 kg/m^3 in Jabalpur.

Spatial analysis of water productivity in three agro-climatic regions of Sabarmati Basin showed that there is significant variation in physical water productivity and water productivity in economic terms (gross and net) of irrigation water across different agro-climatic regions for all the four crops selected from Sabarmati River basin. For instance, water productivity in physical terms for wheat ranged from 0.71 kg/m^3 in Daskroi to 2.75 kg/m^3 in Bayad. The water productivity in economic terms (gross) ranged from Rs. 4.66/m^3 in Daskroi to Rs. 18.39/m^3 in Bayad. The net water productivity for wheat for the same locations ranged from Rs. 1.38/m^3 to Rs.4.66/m^3. Similar variations in physical productivity of water were found for castor oil between Himmatnagar and Kapadwanj. The physical productivity of water ranged from 0.66 kg/m^3 to 1.62 kg/m^3. The gross economic water productivity ranged from Rs. 9.69/m^3 in Himmatnagar to Rs. 25.57/m^3 for Bayad. The net economic water productivity ranged from Rs. 3.56/m^3 in Himmatnagar to Rs. 16.4/m^3 for Bayad. Interestingly, unlike in the case of wheat which gave the highest physical productivity of water and also gave the highest water productivity in economic terms, in case of castor oil, the locations which gave the highest economic water productivity did not coincide with those of the highest physical productivity of water.

Ways to Enhance Irrigation Water Productivity in Economic Terms

Improving Water Control and Its Potential Impact

The analyses presented in the earlier sections clearly show that water productivity is a function of applied water; and dosage of fertilizers, and that it can be manipulated through water control. It is based on the premise that in many situations farmers do not have control over water delivery and fertilizer dosage, or else are tempted to apply more water to maximize the yields and returns per unit of land. The lack of control over water delivery could be either due to lack of physical control over water delivery or due to lack of sufficient water to irrigate. The tendency to apply water or fertilizer in the low productivity regime could be due to two reasons:

1) Farmers are not able to make correct judgments about water allocation for maximizing the aggregate returns (which is the multiple of net returns per ha of the crop, and total area of the irrigated crop), due to lack of correct information about the levels of irrigation that result in the maximum net return per unit of land, and which enables maximizing the area irrigated.

2) Farmers are not confronted with either marginal cost or opportunity cost of using excess water.

In the process, they are not able to get optimum level of yield that gives the highest water productivity.[3] To what extent 'water control' interventions would help enhance water productivity depends on the shape of the yield and water productivity response curves of the crop in question to irrigation inputs. It would also depend on what fraction of the applied water is actually used for non-beneficial depletion from the crop land. We do not have any information about non-beneficial depletion from the applied water. But the major sources of non-beneficial depletion are a) the deep percolation, which is either lost in the vadose zone,[4] or which joins the saline aquifer; b) the evaporation of soil moisture after crop harvest during the fallow period; c) direct evaporation from the soil surface, especially during crop establishment and d) possibly unnecessary watering at the end of the season when it does not contribute to the yield.

We have seen three different types of responses of yield and water productivity to irrigation dosage. We discuss the strategy for enhancing WP in each of these cases. In the first situation: a) the relationship between applied water and yield is positive, but weak; and b) the response of water productivity to applied water is inverse and exponential. In such situations, the reduction in dosage of irrigation water would not affect the yield significantly; and the effect often may not even be adverse. But the same would enhance water productivity significantly. But, this strategy would work only if there is sufficient amount of arable land, which remains uncultivated due to shortage of water. The reason is the water saved from the field can be diverted to expand the area under irrigation.

The second situation is one in which the relationship between applied water and yield is strong and positive, wherein most farmers are applying water under scarcity regime and very few under water abundance regime (Figures 4, 5 and 6). Then, it is likely that with an increase in dosage of irrigation, the physical productivity of water also might increase slightly. But, the water productivity (Rs/m^3) response to applied water is 'inverse-logarithmic'. Here, the best strategy for most of the farmers would be to minimize the irrigation dosage, which would help obtain the highest water productivity in economic terms. Here, it may be necessary for the farmers to expand the area under irrigation slightly to maintain the net returns.

In the third situation, the relationship between applied water and yield is 'polynomial', where yield increases with irrigation dosage up to a certain point, and then declines. This is the situation found in the case of irrigated cotton in West Nimar District (based on Figure 7). In such a case, with increasing dosage of water, the productivity would decline abruptly beyond the point which corresponds to the maximum yield. Hence, the relationship between applied water and water productivity is 'polynomial'. This is the most ideal situation where those farmers who are losing on the yield and income returns have an incentive to reduce irrigation dosage, by which they could enhance both yield and water productivity. The reason why it occurs is the zero marginal cost of electricity used for groundwater pumping owing to the flat rate system of pricing electricity in all the groundwater irrigated states. This mode of pricing creates no

[3] It is also to be noted that water productivity is not an objective for farmers to realize when water is in plenty. On the contrary, they would try to maximize the income returns per unit of land, for which crop yield (kg/ha) enhancement is the best route.

[4] The water which is 'lost in the vadose zone' normally becomes non beneficial E or ET as bare soil evaporation or transpiration through other (non-productive) vegetation.

incentives for farmers to use groundwater efficiently. In such situations, it is not even necessary that farmers expand the area under irrigation to maximize their aggregate returns from farming. But, there are many farmers who are not getting optimum yield and water productivity due to inadequate dosage of irrigation water. It is important for them to reduce the area under irrigation while increasing irrigation dosage to optimize yield and water productivity.

There are many water allocation and control measures to improve water productivity. Water control is possible through either of the two methods: 1) micro-irrigation technologies, mainly for non-field crops; and, 2) establishing water delivery control devices such as storage systems, particularly in the case of surface irrigation systems where water delivery through tertiary canals is not regular. Micro-irrigation systems can help achieve two things: a) improving control over applied water; and b) reducing the non-beneficial depletion of the applied water and maximizing the consumptive use fraction of the applied water. The potential impact of the second intervention would be in limiting the amount each time. This, in a way, also may help reduce non-beneficial depletion but its impact may be less significant as compared with micro-irrigation.

But, we have not come across situations where farmers are not able to secure optimum levels of water productivity due to water shortages. Farmers have reasonably high degree of control over water delivery as they are all well-owners, power supply being the only factor that reduces the control over water delivery. In states such as Punjab, Gujarat and Madhya Pradesh, the quality of power supply in agriculture is poor. The supply is provided in rotations, and sometimes during night hours. They tend to apply heavy doses of water when power supply is available. This may be leading to a situation where the water productivity starts declining as found in most cases, or yield (Rs/m^3) itself starts declining.

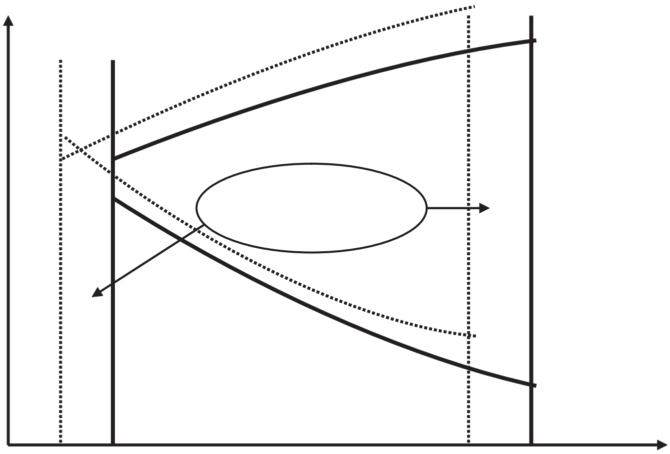
It is quite understandable that farmers do not care about water productivity much. This is in spite of the fact that water availability is extremely limited in some of the areas we have covered in our study like west Nimar and Dhar. Hence, the option of ‘controlling applied water dosage’ for enhancing water productivity would work only in areas where a good part of the cultivable land is kept fallow due to water shortage.

Now, let us look at the option of micro-irrigation. For a given amount of nutrient inputs, the only determinant of the crop yield is the consumptive use of water by the crop (ET) and how far the transpirative requirements of the crop area met during critical stages of crop growth. Using micro-irrigation for row crops, the non-beneficial depletion of applied water could be reduced to nil. Such non-beneficial depletion under traditional method of irrigation would be significant in the case of row crops. Therefore, the twin-objective of achieving higher water productivity and higher yield is possible through micro-irrigation devices. The response curve of yield (Kg/ha) and water productivity in economic terms (Rs/m^3) to irrigation dosage under traditional irrigation and micro-irrigation is given in Figure 9.

It shows that the yield corresponding to the same amount of ‘applied water dosage’ would be higher under micro-irrigation. Or in other words, for the same amount of applied water, the yield would be higher. Research in many parts of India had already shown that for cash crops, particularly those grown in rows such as cotton, the net incremental returns for drip irrigation plots over flood irrigated plots are higher than the sum of capital and operational costs of drip systems.[5] This means that even in situations, where the entire land is irrigated,

[5] Such crops include banana, sugarcane, orange, grapes and cotton.

Figure 9. Response curve of crop yield and water productivity (in economic terms) for applied water under micro-irrigation.



farmers might have incentive to go for micro irrigation for such crops. The water productivity gain automatically comes under such situations.

Changes in Input Use and Potential Impacts on Water Productivity

For a ‘linear response curve’ of yield to fertilizer dosage, the response curve for water productivity (Rs/m^3) may not be inverse exponential or inverse logarithmic; but ‘direct and linear’ as shown in the case of wheat in Hoshangabad for the year 2003 (Figure 9). Inverse relationships can occur only if the fertilizer dosage is accompanied by increased dosage of irrigation. But, with an increase in fertilizer dosage, the water productivity could actually rise, and then decline. This is because it would be possible to increase yields with an increase in fertilizer dosage, without much change in irrigation dosage up to a certain point. But, beyond a point, increased use of fertilizer dosage would require greater dosage of irrigation for increasing the nutrient absorption capacity of the plants, which reduces water productivity. Here adjusting the fertilizer dosage to optimal levels is crucial.

Through this, for the same dosage of irrigation water, crop yield can be enhanced to an extent with optimal dosage of fertilizers. This means that the physical productivity (kg/m^3) of water, apart from returns from land, could be enhanced through manipulation of fertilizer use.[6] This might increase water productivity in economic terms as well as, as seen in the earlier section. Such situation can be encountered in the central India best covering most parts of Narmada, Tapi, Mahi and Krishna basins, where fertilizer use in agriculture is one of the lowest.

[6] But, primary data collected from farmers in Narmada Basin show that with increase in irrigation dosage, there is proportional increase in the dosage of fertilizers in most situations. Hence, the effect of fertilizer on crop yield and water productivity cannot be assessed through multiple regression model estimation procedures.

If fertilizer dosage is in a regime where the yield does not respond positively, then simple reduction in dosage would result in saving of input costs, thereby increasing water productivity in rupee terms. Such situations are possible in Punjab and Haryana where application of nitrogenous fertilizer is excessively high.

Potential Impacts of Improving Quality of Irrigation and Water Allocation

The analysis of Punjab and North Gujarat clearly show that improvement in quality of irrigation would significantly impact on yield (as shown in the case of Punjab) and water productivity (as shown in case of North Gujarat). Here, quality of irrigation includes adequacy and reliability (based on Kumar 2005). With greater reliability and adequacy of irrigation water deliveries, farmers would be able to adopt good agronomic practices and adjust nutrient use. With increasing uncertainty of water, farmers hesitate to apply adequate quantities of fertilizers, thereby compromising on the yield.

In case of farmers who are mainly using canal water for irrigation, it is quite common that the depth of each application is much higher than the optimum dosage decided by the field capacity as compared with those using well water. This leads to heavy percolation losses and reduces the efficiency of storage of water in the soil profile. It leads to excessive residual moisture after harvesting as well, which gets depleted in soil evaporation. Greater dosages may also increase the changes of fertilizer leaching, which leads to reduced nutrient use efficiency. Improving the quality of irrigation in such situation would help farmers optimize the irrigation dosages in each watering and give adequate number of waterings without changing the volume. This would not only increase the yield, but also reduce the wastage in irrigation, thereby enhancing water productivity of not only applied water, but also depleted water.

Allocating Water across Regions and Productivity Gains at the Basin Level

Spatial analyses of crop water productivity in Narmada Basin showed that water productivity of irrigated crops varies significantly across regions with changing agro-climate. The northern hills region of Chhattisgarh has moist sub-humid to dry-sub-humid climate. The four regions, viz., Kymore Plateau and Satpura Hills, Vindhya Plateau, Satpura Plateau and Central Narmada Valley (CNV) have ‘dry sub-humid’ climate. The regions, viz., Malwal Plateau, and Nimar Plain have semi-arid climatic conditions. The district of Jhabua, which falls in the region, named ‘Jhabua Hills’, is ‘semi-arid’[7].

While water productivity variations between two regions for the same crop can also be attributed to differential dosage of fertilizers, differential transpiration ratio and seed varieties, it is assumed here that variations in the same across regions are not significant.

[7] Kumar and Singh 2006 for detailed description of average annual rainfall and reference evapotranspiration in all the nine agro-climatic regions falling in Narmada Basin.

The physical productivity figures are far below the normal figures for wheat in many regions. It was found to be the highest in the northern hill region of Mandla (Rs.1.8 kg/m^3), and the lowest in Jabalpur (0.47 kg/m^3) during a normal year. This difference could be attributed to the difference in agro-climate across regions, which reduces the denominator of water productivity, if we consider the fact that there are no major variations in yield levels between these regions. The variations are larger if one compares water productivity in Punjab. There, farmers obtain a return of 2.33 kg/m^3, irrespective of the aridity which increases irrigation water demand. This may be due to the high yield the farmers secure, with efficient use of water and fertilizers, and with the help of favorable agro-climate for growing winter wheat. The question, therefore, is whether the natural advantage which certain crops enjoy in certain regions in terms of higher water productivity by virtue of the agro-climate can be made use of, without compromising on farmers' need and priorities. This means, earmarking certain crops only in those regions where they have relative advantage in terms of getting high water productivity—both physical productivity and productivity in economic terms.

Potential for Improving Irrigated Water Productivity in India

Possible Crops and Areas for Increasing Irrigated Water Productivity

Regions which receive intensive canal irrigation are regions that should get priority in water productivity improvements because of 1) the water-intensive crops grown in these regions; 2) 'poor water delivery control'; and, 3) poor quality of irrigation. But, the regions should be such that irrigation water management practices comprising water delivery control and improvement in quality of irrigation result in reduction in non-beneficial evaporation. Therefore, semi-arid and arid regions with low water table conditions are ideal for this.

It is a general notion that water productivity is generally high in regions such as Punjab and Haryana, which receive extensive and intensive canal irrigation. This is based on high yield levels obtained for wheat and paddy in these regions. These regions are also known for intensive cropping of wheat and paddy. Our analysis for Punjab suggests that there is ample scope for improving yield in wheat and paddy through improving the quality of irrigation in terms of adequacy and reliability. In Punjab, such improvement of canal water supplies would lead to greater yield for wheat and paddy, apart from reducing non-beneficial depletion and improving water productivity. Hence, Irrigation Department should have incentive to go for improving both adequacy and reliability (quality) of irrigation water, and water delivery control. Since the area that can be irrigated cannot be expanded, it would lead to reduction in groundwater draft as well.

Groundwater irrigated areas, where a substantial area is still left uncultivated due to water scarcity, should receive attention for water productivity enhancements. The reason is it makes economic sense for the farmers as they can expand the area under irrigation and increase aggregate returns. The priority areas would be hard rock areas of peninsular, central and western India. A wide variety of crops are being grown in these regions such as cotton, castor, groundnut, mustard, banana, sugarcane, potato, and cereals such as paddy, *bajra* and sorghum. Among these, the water-intensive ones that are grown in large areas are paddy, cotton, sugarcane, banana, cotton, castor, groundnut, and potato. In crops such as paddy, water productivity enhancement has to come through ‘water control’[8] and ‘improving the quality of irrigation’. Wheat would be another crop which should receive attention in western Gujarat, Maharashtra and Rajasthan, and Central India. Such enhancement would come mainly from achieving ‘water control’.

In case of crops such as cotton, groundnut, potato, castor, banana and sugarcane, it can also come from the use of micro-irrigation devices, especially in sandy soils as it is very difficult to maintain high distribution uniformity in water application with traditional methods of irrigation such as level borders and furrows. Large-scale adoption of drip irrigation for banana and sugarcane in Maharashtra and for potato, groundnut, cotton and castor in North Gujarat bears testimony to this. Some recent analysis by Narayanamoorthy 2004 and Kumar et al. 2004 justify farmer investment on drip irrigation for banana and sugarcane. If it is so, enhancement in water productivity through micro-irrigation devices would be much higher than that through water delivery control.

Potential Improvements in Water Productivity at the Basin level

We have seen that the levels of water productivity achieved by most farmers in the sample from the three basins, viz., Indus, Ganges and Narmada, are much less than the maximum potential. We have also seen that there is some scope for raising the productivity of applied water in India for several crops through ‘water delivery control’”. But, under this approach, the productivity improvement comes from reduction in yield, resulting from reduction in consumptive use of water. The gain in applied water productivity results in the same extent of gain in productivity of depleted water only in semi-arid and arid regions where the depth to groundwater table is large.[9] and where non-beneficial evaporation from fallow is high. Hence, only in such regions where a significant portion of the applied water is depleted, there would be basin level productivity gains through water delivery control.[10] But, for farmers to go for water delivery control measures, they must have extra land to maintain the farm returns.

Though micro-irrigation would raise crop water productivity both in physical and economic terms without reducing yield (as illustrated by Figure 13), the impact of micro-irrigation again would be significant in arid and semi-arid areas, and for row crops. This is because in the case of row crops evaporation component of consumptive use of water by crop (ET) is quite large, especially under aridity. Again, the area under row crops is very small in the sub-humid and humid areas and water abundant areas.

The peninsular India and western India have substantial area under crops that are conducive to micro-irrigation technologies. Adoption of MI systems would lead to basin level

---

[8] We refer to only water delivery control and possibility of water control through micro-irrigation is ruled out.

[9] Deep groundwater table and aridity means that the return flows from applied water are not significant; and evaporation of residual soil moisture from fallow is very high.

[10] In sub-humid and humid regions with shallow water-table, basin level water productivity gain would be very much lower.

water productivity improvements. Uttar Pradesh accounts for nearly 2 5% of the area that can be potentially brought under WSTs from 16 major states of India. But, the likely rate of adoption of WSTs in this state is going to be poor due to rural infrastructure, particularly rural electrification; relative water abundance; shallow groundwater in most areas; and very low size of operational holdings of farmers. Even if this region adopts WSTs on a large-scale, it may result not in reduction in depleted water, but a little difference in crop yields, with the resultant increase in basin level water productivity being meager. Western part of Mahanadi is another area that would be conducive to WSTs.

If we keep these considerations, the basins that are conducive to measures for improvement in water productivity through water control (comprising 'water delivery control' and 'micro-irrigation') are 1) all east-flowing rivers of peninsular India; 2) west-flowing basins north of Tapi in Gujarat and Rajasthan; Mahanadi; some parts of Indus Basin covering south-western Punjab; and west- flowing rivers of South India. The basins that are not conducive to water control measures are Ganga, Brahmaputra and Meghna. But, there are areas such as Bihar, eastern UP and Assam, where the crop yields are currently low. Increase in use of nitrogenous fertilizers and high-yielding varieties would help enhance the crop yields significantly. With no changes in the consumptive use of water, this could create major changes in water demand drivers. Due to economic scarcity of water,[11] farmers in Bihar would have incentive to enhance the return per unit of pumped water.

There are many regions in India where water productivity is not a consideration for individual farmers, though the economy would benefit a lot by reducing the amount of water depleted and the energy used for growing crops. These are groundwater irrigated areas where there are no physical or economic constraints on the amount of water farmers can pump. In these areas, farmers want to maximize the returns per unit of land as their entire land is already irrigated. Such areas include parts of Indus in central Punjab, Haryana and UP. In these areas, water availability is not a constraint in maximizing farm returns, but land availability is. In such areas, water productivity improvement measures should help raise income returns from every unit of land irrigated. Hence, the only option to enhance water productivity available is water delivery control, and can be used in situations where excessive irrigation leads to yield losses.

Implications of Water Productivity Change on Water Demand Drivers

Enhancement in applied water productivity through 'micro irrigation', would have significant implications for water demand in agriculture per unit area of cultivated land in semi-arid and arid area, if the depth to groundwater table is large or the aquifers are saline. But, it will have least effect in sub-humid and humid areas. But, in semi-arid and arid areas, the farmers would use the saved water to expand the area under irrigation to maximize their aggregate returns in the presence of sufficient uncultivated land, and as a result the aggregate demand for water may not change.

On the other hand, reduction in non-beneficial depletion of water through 'water delivery control' would nevertheless be high in arid and semi-arid areas with deep groundwater tables. But, here again, farmers would expand the area under irrigation, as their returns per unit area would decline. The result would be no reduction in aggregate demand for water. Exceptions

[11] Many marginal and small farmers pay very high charges for pump rental services for irrigating crops.

would be those in which farmers water their crops in excess of the crop requirement leading to yield losses. On the other hand, in sub-humid and humid and cold climates with shallow groundwater conditions, the reduction in non-beneficial depletion would be much less. This is because, with increase in dosage of water under traditional methods of irrigation, the amount of water which is available as return flows as a percentage of the total water applied would be higher. Examples are eastern region of India where groundwater table is very shallow. But, in such areas, it is very unlikely that farmers adopt measures which are at the cost of yield reduction. Hence, no reduction in aggregate demand for water is expected in such basins also.

At the same time, in sub-humid and humid areas having plenty of water—either surface or groundwater—the enhancement in applied water productivity through manipulation of fertilizer and crop technology inputs can reduce the irrigation water supply requirement per unit area if the yields are just to be maintained at the current level. Such outcomes are extremely valuable in view of the fact that there are millions of farmers in this area, who are still dependent on purchased water for irrigating their crops. But, in practice, with the adoption of high yielding varieties and increased fertilizer dosage, farmers would proportionally increase the dosage of irrigation. Therefore, the aggregate demand for irrigation would go up even if one does not anticipate any change in area under irrigation.

Conclusion

Overall, the empirical evidence provided from three important river basins shows that: a) there are major variations in physical productivity of water and water productivity in economic terms across farmers in the same area; b) the same crop grown in different regions has remarkably different levels of physical productivity of water and water productivity in economic terms; and, c) the same crop has differential water productivity with different qualities of irrigation water applied. The variation in water productivity (Rs/m^3) for the same across farmers in the same location was explained by the following facts: 1) most farmers are applying water within a regime where the yield response to both irrigation and fertilizer dosage is positive; and 2) water productivity response to irrigation is negative. Nevertheless, in certain situations, the water application regime of farmers corresponds to a regime where both yield and water productivity responses to irrigation are either positive or negative. In sum, the water productivity realized by farmers is much less than the maximum potential.

Following are the four major ways of enhancing crop water productivity: a) water control comprising 'control over water delivery' and micro-irrigation; b) improving quality (adequacy and reliability) of irrigation; c) manipulating other inputs, mainly fertilizers; and d) earmarking certain crops only for those regions where they have relative advantage in terms of getting high water productivity. But, in most situations, trade-offs exist between enhancing water productivity in economic terms and crop yields through water delivery control. Due to this trade off, farmers would have incentive to pursue water productivity improvement measures only if extra land is available, so as to divert the saved water to expand the area under irrigation and sustain the aggregate returns.

Field level water productivity improvements through water delivery control and use of micro irrigation, together called 'water control', would result in basin-level water productivity improvement in basins falling in semi-arid and arid regions of India with deep water table conditions. But, this would not result in water-saving at the basin level. Situations where both basin-level water productivity enhancement and real aggregate level water saving, occur due to water control are quite rare.

References

Abdulleev, I.; Molden, D. 2004. Spatial and temporal variability of water productivity in the Syr Darya Basin, Central Asia. *Water Resources Research*, Vol. 40, W08S02.

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; D. Molden; R. Barker. Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Keller, A.; Keller, J.; Seckler, D. 1996. *Integrated water resources systems: Theory and policy implications.* Research Report 3, Colombo: International Water Management Institute.

Kijne, J. W.; Tuong, T. P.; Bennett, J.; Bouman, B.; Oweis, T. 2002. Challenge Program on Water and Food-Background Papers. Consultative Group on International Agricultural Research.

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

Kumar, M. D.; 2005. Impact of Electricity Prices and Volumetric Water Allocation on Groundwater Demand Management: Analysis from Western India. *Energy Policy*, 33 (1).

Kumar, M. D.; Singh, K.; Singh, O. P.; Shiyani, R. L. 2004. *Impacts of water saving and energy saving irrigation technologies in Gujarat*. Research Report 2. India Natural Resources Economics and Management Foundation, Anand, India.

Kumar, M. D.; Singh, O. P. 2006. Blue and Green Water Use and Productivity in Agriculture: A Study of Narmada River Basin in Madhya Pradesh, India. Proceedings of the 3rd Conference of the Asia Pacific Association of Hydrology and Water Resources. Bangkok, October 16-18, 2006.

Molden, D.; Murray-Rust, H.; Sakthivadivel, R.; Makin, I. 2003. A Water Productivity Framework for Understanding and Action. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, Comprehensive Assessment of Water Management in Agriculture, eds. J.W. Kijne; D.Molden; R. Barker. UK: CABI Publishing in Association with International Water Management Institute.

Molden, D.; Sakthivadivel, R.; Habib, Z. 2001. *Basin-level use and productivity of water: Examples from South Asia*. IWMI Research Report 49, Colombo: International Water Management Institute.

Narayanamoorthy, A. 2004. Drip irrigation in India: Can it solve water scarcity? *Water Policy*, 6 (2004): 117-130.

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

Xie, M.; Kuffner, U.; Le Moigne, G. 1993. Using Water Efficiently, Technological Options. Technical Paper 205. Washington D.C: World Bank.