WATER PRODUCTIVITY OF IRRIGATED AGRICULTURE IN INDIA: POTENTIAL AREAS FOR IMPROVEMENT

M. Dinesh Kumar[1], O.P. Singh[2], Madar Samad[3], Hugh Turral[4] and Chaitali Purohit[5]

Abstract

The objective of the study is to explore the scope for water productivity enhancement in irrigated agriculture in India through: i] water control; ii] optimizing nutrient input to crop; iii] improving the quality and reliability of irrigation water; and, iv] growing crops in regions where climate is favourable. The study is based on data from three important river basins in India, viz., Indus, Narmada and Sabarmati. The study involved: 1] estimating the incremental water productivity of selected crops viz., wheat and cotton in response to applied water, and fertilizer dosage; 2] estimating water productivity of the same crop across agro-ecological zones within the basin, and 3] comparing determinants of crop water productivity with different sources of irrigation with differential reliability and quality.

Most farmers are applying water within a regime where the yield response to both irrigation and fertilizer dosage is positive. Also, their water application corresponds to a regime where water productivity (Rs./m^3) response to irrigation is negative and fertilizer is positive. But, in certain situations, farmers' water application regime corresponds to a regime where both yield and water productivity responses to irrigation are either positive or negative. Within basins, for the same crop, water productivity in both physical and economic terms is much higher in high rainfall, sub-humid area as compared to that in low rainfall, arid areas. The quality and reliability of irrigation can significantly impact the type of crops chosen by farmers and the crop yield, thereby raising water productivity.

There is ample scope for improving water productivity in irrigated agriculture through water control. But, in most cases, it may lead to reduced net return per unit of land. Hence, they would have incentive to go for water control measures only if there is sufficient land, which can be put to use for irrigated production using the saved water.

1. 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 increasing 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. 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 (Molden et al., 2003). The classical concept of irrigation efficiency used by water engineers omitted economic values and looked at the actual evapo-transpiration (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).

At the field level, there is no single parameter to determine the efficiency of water use in crop production. Measures to enhance yield to raise water productivity in biomass per unit of water depleted, might increase the cost of production thereby reducing net return per unit of water depleted. Therefore, crop water productivity needs to be assessed in terms of both kilogram of crop per cubic metre of water diverted or depleted (Kg./m^3); and net or gross present value of the crop produced per cubic metre of water (Kijne et al., 2003).

---

[1] Researcher and ITP Leader, International Water Management Institute, Patancheru, Andhra Pradesh, India; E-mail: d.kumar@cgiar.org

[2] Agricutural Economist, Department of Agricultural Economics, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi – 221 005, E-mail: singhop@bhu.ac.in ; ompsingh@gmail.com

[3] Principal Researcher and Head India Office, International Water Management Institute

[4] Formerly Principal Scientist, IWMI, Sri Lanka

[5] Formerly Junior Consultant, IWMI, India

While the yield would increase with an increase in actual ET, the water productivity (Rs./m^{3}) would start leveling off and then start declining much before the yield reaches maximum (see for instance Molden et al., 2003). The reason is that the amount of depleted water might increase with increase in irrigation dosage, and beyond a point, it does not result in yield increase (Vaux and Pruitt, 1983). Similarly, while the yield would keep increasing until a point with increase in nutrient inputs, the net return might start decreasing even at level of nutrient dosage lower than that corresponding to maximum yield. Hence, the challenge is to identify optimum level of water and nutrient inputs to ensure maximum return per unit of land and water. The measure can be referred to as "water control"; and optimizing nutrient dosage, respectively.

"Water control" refers to supplying water dosages close to the difference between crop water requirement and available soil moisture in the root zone. It ensures greater utilization of applied water for ET, and minimal non-recoverable percolation from the applied water, which is non-beneficial. It also reduces the fraction of non-beneficial evaporation from applied water. Hence, with controlled water delivery, the yield would be more for the same depletion or consumed fraction, resulting in higher water productivity.[1] The measures for this include on-farm water management practices and improving the conveyance of water. Micro irrigation systems take care of water control for many crops, and in certain other crops by farm leveling.

Crop water productivity also depends on the reliability and quality of irrigation water applied in addition to control over water delivery. Improved reliability can ensure better timing of irrigation to ensure crop growth needs (Meinzen-Dick, 1995). With the same amount of water applied, the crop consumptive use (ET) would change depending on the timing of water application. On the other hand, 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 and reliability of irrigation should affect water productivity, with the same amount of irrigation water applied.[2]

Now, opportunities for enhancing water productivity would change when one moves from the field to the basin. Enhancing water productivity at the field through water control may adversely affect the availability of water for downstream uses in a closed basin. The reason is the probable reduction in non-consumptive part of the water applied (Allen et al., 1998; Molle and Turral, 2004). If those downstream uses have higher return per unit water use, water control measures would result in productivity losses at the basin level. On the other hand, at the basin level, as Abdulleev and Molden (2004) note, opportunities might exist for growing the same crop in areas where their ET values are lower, which result in improved water productivity in both physical and economic terms. Hence, crop water productivity needs to be mapped across different agro climates in the basin.

In this paper, the potential for enhancing water productivity in agriculture and water saving are explored in selected river basins of India through the following measures: 1] water control and optimizing nutrient input to crops; 2] improving the quality and reliability of irrigation; and 3] growing certain crops in regions where the ET requirements are lower and genetic potential of the crop can be realized.

2. REVIEW OF LITERATURE ON WATER PRODUCTIVITY IN IRRIGATED AGRICULTURE

Over the past few years, the concept of productivity of water in agriculture has gained ground owing to increasing scarcity of irrigation water from physical and economic perspectives, mostly locally and often also regionally. Several studies are available from the past which deal with water productivity of crops with respect to evapo-transpiration (ET) of crops (see for instance, Table 1, Kijne *et al*., 2002: pp8 and Zwart and Bastiaanssen, 2004). But, we would discuss only those which are relevant for the present study.

Choudhury and Kumar (1980) and Singh and Malik (1983) showed large differences in water productivity of wheat between wet and dry years. Tuong and Bouman (2002), estimated water productivity of rice in India; found it in the range of 0.50-1.10 Kg./m^3 against 1.4-1.6 Kg./m^3 for wet-seeded rice in the Philippines;

---

[1]See Allen *et al.,* (1998) for definitions of consumed fraction (CF), non-recoverable deep percolation, non-beneficial evaporation, consumptive use and ET, and differences thereof.

[2]However, 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.

Oweis and Hachum (2002) analyzed water productivity impact of supplementary irrigation on pulses. Study by Saeed and El-Nadi (1998) in Shambat, Sudan, Utao and Idaho on forage crops showed improvement in physical productivity of water with supplementary irrigation. Rockström *et al*., (2002) provided evidence from Kenya and Burkina Faso to the effect that supplementary irrigation enhances water productivity (Kg./m^3) of rain-fed maize and sorghum, respectively, remarkably with greater effect coming with fertilizer management; and from Tanzania to show that conservation tillage increases water productivity of maize.

Ahmad *et al*. (2002) used Soil Water-Atmosphere-Plant (SWAP) model to estimate water flux in the unsaturated soil profile of groundwater irrigated areas of Pakistan Punjab under rice-wheat system and cotton-wheat system. Singh *et al*. (2003) used the same model to estimate the same for Sirsa district of Haryana. Both the studies quantified the moisture changes in unsaturated soil profile during crop seasons. The studies found that the vertical water flux in the unsaturated zone is continuous under rice-wheat system with frequent and intensive irrigation. Though both the studies showed that a significant amount of the water applied is recycled, they also showed significant build up of moisture in the unsaturated zone, which can be lost in soil evaporation.

It is recognized that the ET values themselves could reduce with better irrigation and soil management (Burt *et al*., 2001), and thereby improving the chances of cutting down groundwater depletion. However, the significance of achieving better groundwater balance through irrigation management increases with decreasing efficiency of conveyance of percolating water from the crop root zone to the groundwater system.[3]

Ahmad *et al*., (2004) estimated the spatial and temporal variations in water productivity (physical and economic) separately for process evaporation, soil evaporation and actual ET which were estimated using SWAP model for rice-wheat area in Punjab. They found that the applied water (sum of precipitation and irrigation) far exceeded the evapo-transpired demand (ET) in case of rice causing deep percolation. Whereas, it fell short of the ET requirements in case of wheat since some of the requirements were met by soil moisture depletion. They also found that the process depletion (transpiration) to produce a unit weight of cereal was slightly lower for rice when compared with wheat.

Abdulleev and Molden (2004) examined the issue of spatial and temporal variations in water productivity in Syr Darya Basin in Uzbekistan and analyzed its economic and equity implications for basin water economy. From the spatial analysis of water productivity, it was found that the water productivity for supplied water (WP_{supply}) and potential evapo-transpiration (WP_{pet}) are higher for private farms. Water productivity of supplied water is much lower than that of PET, indicating the scope for limiting water application. There is significant difference in lowest and highest water productivities indicating the scope for increasing average water productivity within the basin.

The temporal analysis of water productivity for paddy and cotton for three years (1999, 2000 and 2001) showed the following: highest water productivity in case of cotton for both applied water and PET was obtained in low rainfall years. It also showed that the difference between WP_{supply} and WP_{pet} was smaller in low rainfall years, owing to the fact that irrigation water dosage was close to crop water requirement. In the case of paddy, the highest water productivity (WP_{supply} and WP_{pet}) was obtained in 2001, which was a normal year and lowest in 1999. Water productivity for paddy was not high during dry years.

Singh (2004) analyzed composite farming system in north Gujarat consisting of crops and dairying and estimated productivity of applied well water in dairy farming. Kumar (2007) analyzed the composite farming system in north Gujarat, to analyze the applied water productivity in dairy production. It also analyzed the extent to which groundwater use in the region can be reduced without compromising on the farm economy and milk production through efficient irrigation water use technologies using a simulation model based on linear programming.

To summarize, past research on water productivity were on analyzing average physical productivity of water for select crops, including variation according to climate. There is limited analysis of marginal water productivity (Kg./ET) in response to supplementary irrigation and change in depleted water. However, the economic dimensions of water productivity were not analyzed. Analyses of incremental changes in water

[3]The conveyance efficiencies would be low when the unsaturated zone is very deep due to loss of soil moisture through evaporation, and non-recoverable deep percolation.

productivity of crops in economic terms in response to changes in irrigation water dosage, or ET, were not attempted. It is crucial to assess the potential for improving water productivity of a particular crop and deciding on allocation priorities between crops.

3. OBJECTIVES OF THE STUDY

The objective of the study is to explore the scope for water productivity enhancement in irrigated agriculture in India through: i] water control; ii] optimizing nutrient input to crop; iii] improving the quality and reliability of irrigation water; and, iv] growing crops in regions where climate is favourable.

3.1 Hypothesis

1) Better reliability and adequacy of irrigation can improve yield and water productivity of irrigated crops through better agronomic practices and better water management
2) Better control over water and fertilizers can ensure water productivity improvements in irrigated crops, as water application regime might correspond to either ascending or descending water productivity response curve to irrigation and nutrient inputs.

3.2 Approach and Methodology

The potential for improving water productivity through water control and optimum nutrient use is assessed by estimating: 1] the incremental changes in water productivity (for select crops) with increase in irrigation water allocation and fertilizer inputs. The potential for improving water productivity using climate advantage is assessed by mapping the spatial variation in average productivity of crops vis-à-vis agro-climatic regions. The potential for raising water productivity through improvement in quality and reliability of irrigation is analyzed by comparing average water productivity with different sources of irrigation, which represent different degrees of control over water delivery.

The regions of the study basins are shown in Map 1. The approach is that of primary surveys in the study area. Three river basins in India were selected for the study. They are Indus; Narmada; and Sabarmati.

The study analyzed water productivity variations across: 1] farms growing the same type of crops with same pattern of irrigation; and 2] irrigation sources (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 crops, the sample size is 30-35 for each agro-climate within a river basin. In addition, there were samples for each type of irrigation source. Hence, the maximum sample size was 90 in one location; but limited to only situations where sufficient samples for different modes of irrigation were available. The detailed sampling design is given in Table 1.

Table 1: Sampling Design for Water Productivity Study

Name of the Basin	No. of Locations	No. of Agro climates	No. of Different sources of Irrigation	Total Sample Size
Indus basin	3	3	3 (wells; conjunctive use; canals)	200
Narmada	9	7	1 (wells only)	450
Sabarmati	6	3	1 (wells only)	180

3.2.1 *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, Narmada and Sabarmati. From the Indus, only 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, labour, fertilizer and pesticides, quantum of irrigation water, and quantity (weight in Kg.) and market price (Rs./Kg.) of main and byproduct of the crop output. In addition, discharge of irrigation wells (litre/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 for each crop and for each season were obtained from the farmers.

3.2.2 *Analytical Procedure*

The physical water productivity $\sigma_{irri,i}$ (Kg./m³) and water productivity in economic terms, $\theta_{irri,i}$ (Rs./m³) in a purely irrigated crop i are estimated as:

$$\sigma_{irri,i} = \frac{\nabla_{irri,i}}{1000\Delta_{irri,i}} \; ; \; \theta_{irri,i} = \frac{NR_{irri,i}}{1000\Delta_{irri,i}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \; 1, 2$$

$\Delta_{irri,i}$, and $\nabla_{irri,i}$ are the irrigation water dosage (mm) and yield (Kg./ha.) for purely irrigated crop, 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 Narmada basin, winter wheat in 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.[4]

Marginal physical productivity of water, $\sigma_{comb-irri,j}$ (Kg./m3), and marginal water productivity in economic terms $\theta_{comb-irri,j}$ (Rs./m³) for crops, which receive supplementary irrigation, and have rain-fed yields, with respect to irrigation, are estimated as:

$$\sigma_{comb-irri,j} = \frac{\nabla_{comb-irri,j}}{1000\Delta_{comb,j}} \; ; \; \theta_{comb-irri,j} = \frac{NR_{comb-irri,j}}{1000\Delta_{comb,j}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \; 3, 4$$

Where, $\nabla_{comb-irri,j}$ is the yield corresponding to irrigation water applied (Kg.) and $\Delta_{comb,j}$ is the irrigation water applied for the crop (mm). $NR_{comb-irri,j}$ is the net return per unit area corresponding to the irrigation water applied for the same crop (Rs./ha). $\sigma_{comb-irri,j}$ and $\theta_{comb-irri,j}$ 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

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

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 evapo-transpirative 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 were considered for this methodology, as it had rain-fed yield in many locations.

4. SCOPE FOR ENHANCING IRRIGATION WATER PRODUCTIVITY IN AGRICULTURE

4.1 Using water control for improving irrigation water productivity

In order to assess the potential of "water control" in improving crop water productivity, the incremental changes in crop yield and crop water productivity with respect to irrigation were analyzed. For this, 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; and, 3] the yield response to fertilizer use.

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 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 dosage of irrigation water. However, for the same level of irrigation, the yield differences across farmers are quite substantial. This can perhaps be explained by the difference in fertilizer use by these farmers, differences in soil quality, changes in date of sowing, and differences in crop variety.

Figure 1: Yield vs. Irrigation Dosage in Wheat (Hoshangabad 2002)

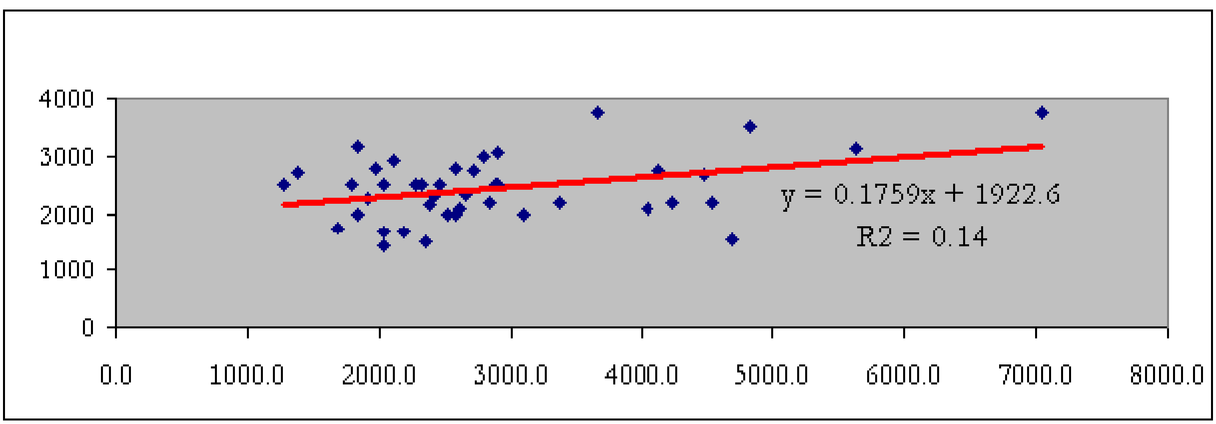
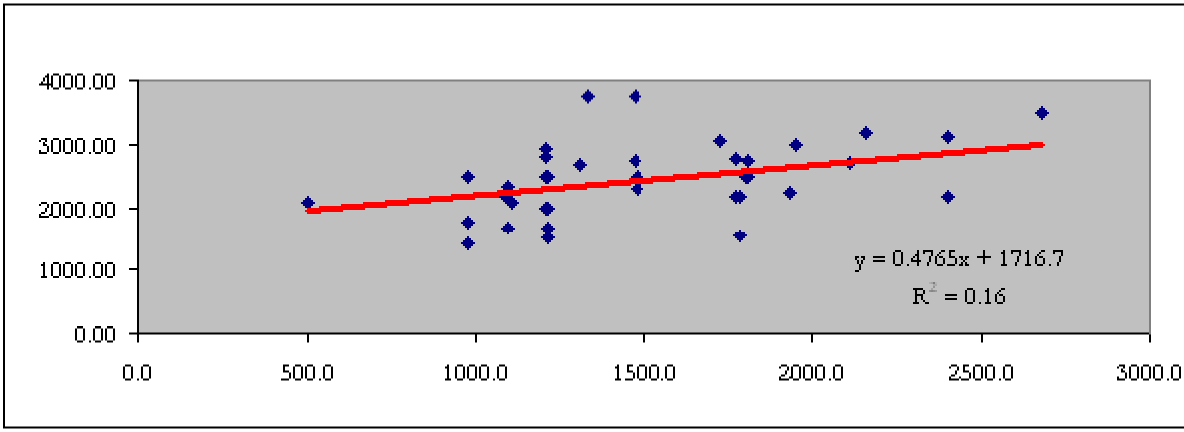


Figure 2 shows the graphical representation of the variation in yield with differential levels of fertilizer input. It shows a slightly stronger relationship between fertilizer use and crop yield (R^2=0.16). Higher dosage of fertilizer meant higher wheat yield. This does not mean that it is the higher fertilizer dosage, which caused higher yield. Generally, it is the farmers who have good irrigation facilities and who use higher quantum of irrigation water use 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 (Hoshangabad 2002)



It was found that two farmers applying the same dosage of irrigation (1834 mm) applied different quantities of fertilizers (worth Rs.1213/ha and Rs. 2160/ha, respectively) and got different levels of yield (19.8 quintal/ha and 31.7 quintal/ha, respectively). In another case, two farmers applied same dosage of irrigation (2035mm), but applied fertilizers in varying doses (worth Rs. 975/ha and Rs. 1205/ha respectively), and got different yields (1480 Kg./ha and 2500 Kg./ha respectively).

Figure 3: Water Productivity vs. Irrigation Dosage in Wheat (Hoshangabad 2002)

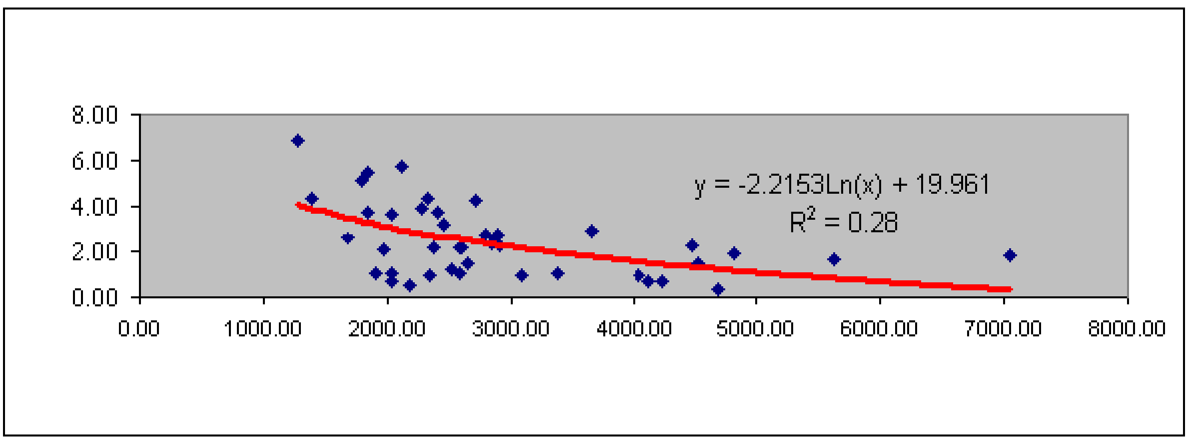
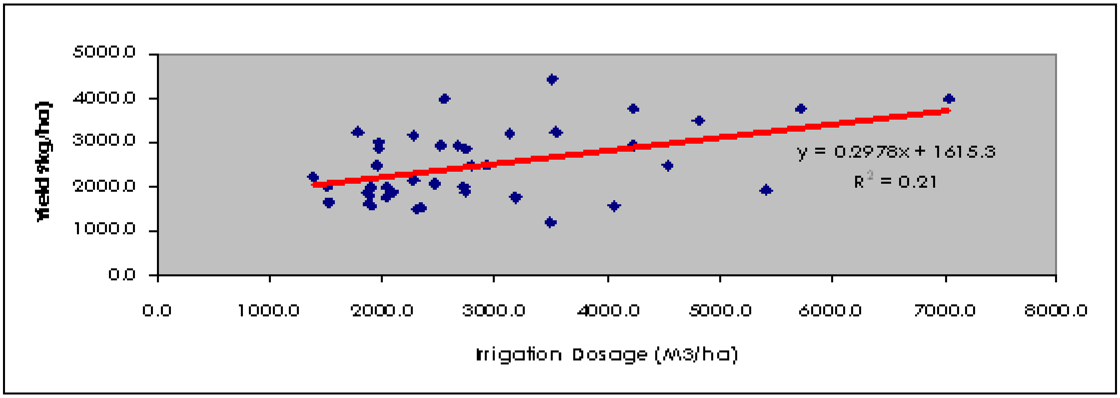


Figure 1 also meant that many of the farmers are applying scarcity irrigation and could have actually got higher yield had they applied higher dozes of irrigation with proportional increase in fertilizer inputs. However, the amount of water applied to the soil also influences the nutrient absorption capacity of the plants, and therefore, irrigation water shortage might be limiting farmers' ability to apply adequate quantities of fertilizers. Mostly, 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). This could be due to the lower levels of fertilizer inputs, which reduced the crop yields. 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.

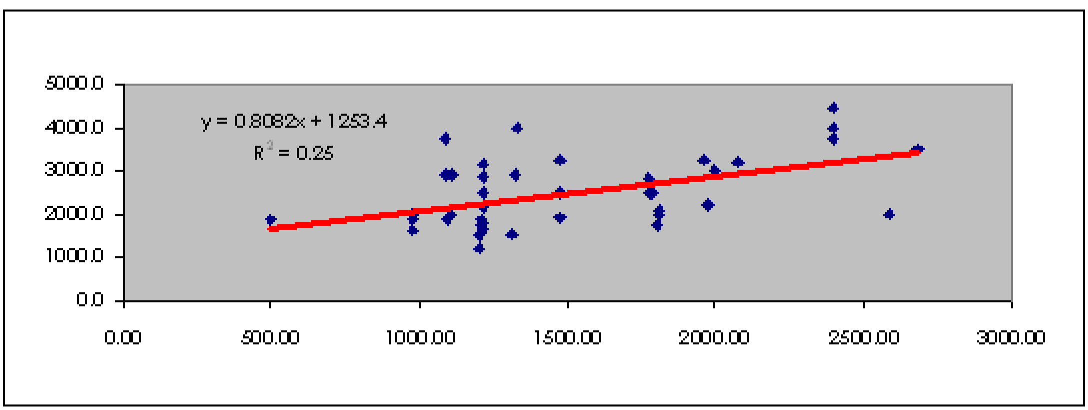
The analysis was repeated for the 2003. It showed a stronger positive linear relationship between applied water and crop yield in wheat (R^2=0.21). Higher levels of water dosage generally ensured higher yield (Figure 4). The incremental yield due to increase in dosage of irrigation by 100 mm was around 230 Kg./ha. Again, there were significant yield differences between farmers who applied more or less 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^2 value of 0.25) confirms to this (Figure 5).

Figure 4: Yield vs. Irrigation in Wheat (Hoshangabad-2003)



Now, the regression values for the response of yield to irrigation dosage being very small (Figure 1 and Figure 4). So, one could argue that many factors other than irrigation explain yield variations. But, given that the data presented here are for different farmers, who represent different soil conditions, different planting dates and different seed varieties, all of which have a potential to influence the crop yield, the relationship and regression coefficient is significant5 . Also, the slope of 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.

Figure 5: Yield vs. Fertilizer Dosage in Wheat (Hoshangabad-2003)

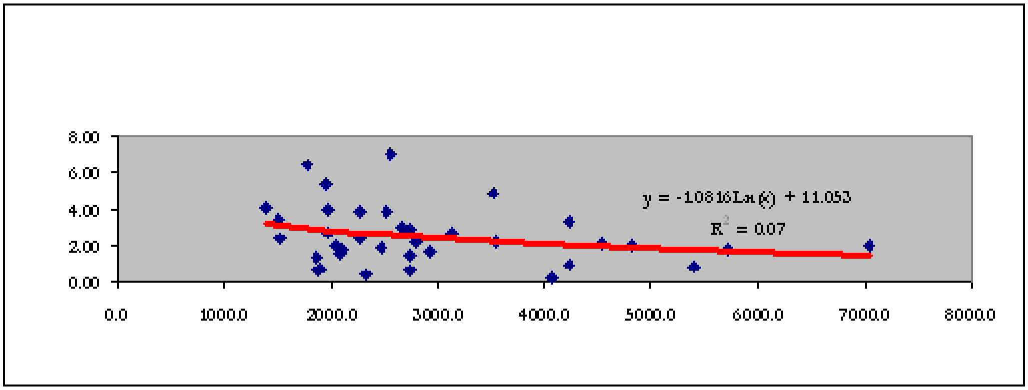


The regression between water dosage and water productivity (Rs./m^3) showed a poor inverse relationship between the two unlike what was found for 2002 (Figure 6). This could be due to the reasons explained above for the same crop grown during 2002. Some of the farmers who were in the lower range of irrigation dosage (between 200 mm and 300 mm) got very low water productivity values (between Rs. 0.41/m^3 and Rs. 1.38/m^3), while 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) are shown by Figure 5.

[5]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.

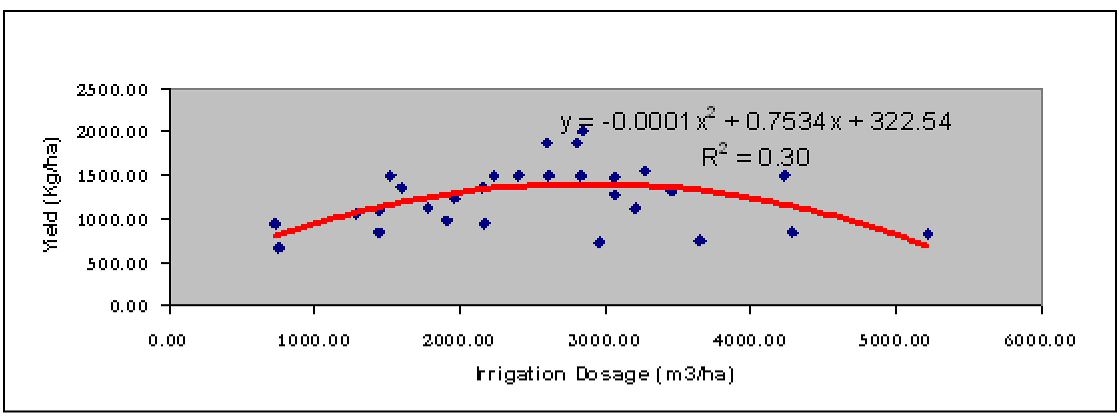
A closer look at the chart showing relationship between irrigation dosage and crop yield also provide better clues to this effect. There are many examples of farmers applying similar dosage of irrigation, but different dosage of fertilizers and getting different levels of yield. For instance, two farmers who applied irrigation dosages of 2518 and 2557 m^3 of water to their wheat, applied different levels of fertilizers (worth Rs.1112/ha and Rs. 2400/ha) and in turn got yields of 2910 Kg/ha and 4000 Kg/ha, respectively.

Figure 6: Water Productivity vs. Irrigation Dosage in Wheat (Hoshanganad-2003)



The analysis was repeated for west Nimar in Narmada basin, for cotton for 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 100mm to 300mm), and then declining. Many farmers who applied close to 300 mm got highest yields. Beyond 300mm, 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 of optimum yield, increase in irrigation dosage led to declining water productivity. This is the third set of response curves (Figure 7).

Figure 7: Yield vs. Irrigation Water Dosage in Cotton (West Nimar 2003)

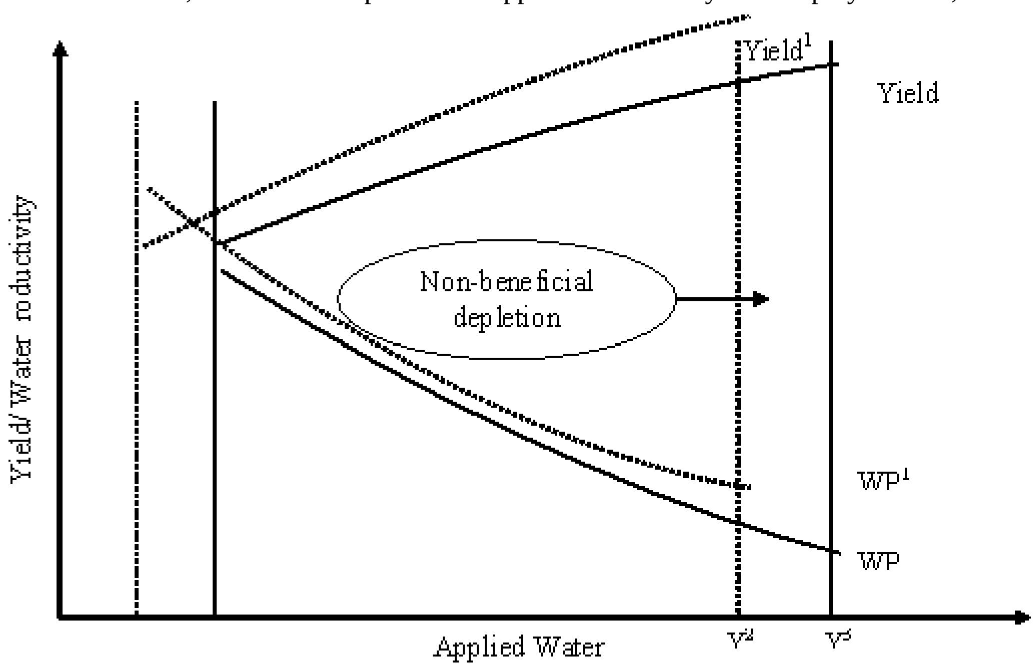


The foregoing analyses show that water productivity can be manipulated through water control. It is based on the premise that in many situations farmers do not have control over water delivery and fertilizer dosage, or are tempted to apply more water to maximize yields and returns per unit of land. In the process, they are not able to get the optimum yield that gives highest water productivity.[6] To what extent "water control" would help enhance water productivity depends on that point of yield and water productivity response curve to which, the irrigation dosage corresponds. It would also depend on what fraction of the applied water from the crop is used for non-beneficial evaporation. We do not have any information about non-beneficial depletion from applied water. Some of the sources are: a] the deep percolation, which is lost in the vadose zone;[7] 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 un-necessary watering at the end of the season when it does not contribute to yield.

There are three different types of responses of yield and water productivity to irrigation dosage. In the first situation: a] the relationship between applied water and yield is positive, but weak; and b] the response of WP to applied water is inverse and exponential. In such situations, the reduction in dosage of irrigation water would not affect the yield significantly; and often the effect may not even be adverse. The same would significantly enhance WP. However, this strategy would work only if there is sufficient arable land, which remains uncultivated due to shortage of water. The reason is that farmers would like to expand area under irrigation and use the water saved from field to irrigate additional land to maintain income returns.

The second situation is one in which the relationship between applied water and yield is strong and positive, where in most farmers are applying water under scarcity regime and very few under water abundance regime (Figure 4, 5 and 6). It is likely that with increase in dosage of irrigation, the physical productivity of water also might increase slightly. However, the response of water productivity in economic terms (Rs./m^3) 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 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.

Figure 9: Potential Changes in Crop Yield and Water Productivity under Micro Irrigation



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 (Figure 7). In such a case, with increasing dosage of water, water productivity declines abruptly beyond the point, which corresponds to the maximum yield. Hence, the relationship between applied water and water productivity in economic terms is "polynomial" (Figure 8). This is the ideal situation where farmers who are losing on the yield and income returns have an incentive to reduce irrigation dosage. By doing this, they enhance both yield and water productivity. The reason

[6]Water productivity is not an objective for farmers to realize when water is in plenty. On the contrary, they would try and maximize the income returns per unit of land, for which crop yield (Kg./ha) enhancement is the best route.

[7] Water "lost in the vadose zone" normally becomes non beneficial E or ET as bare soil evaporation or transpiration through other (non-productive) vegetation.

for over irrigation of crop beyond the point of maximum return is zero marginal cost of electricity used for groundwater pumping owing to flat rate system of electricity pricing in the regions under study. In such situations, it is not even necessary that farmers expand the area under irrigation to maximize their aggregate returns from farming. There are many farmers, who are not getting optimum yield and water productivity due to inadequate irrigation dosage. It is important for them to reduce the area under irrigation while increasing irrigation dosage to save water8 .

Now, let us look at the option of micro-irrigation. For a given amount of nutrient inputs, the only determinant of crop yield is ET and how far the transpirative requirements of the crop area met during critical stages of crop growth. Under micro irrigation, non-recoverable deep percolation is negligible. Further, the non-beneficial evaporation of applied water can be reduced to nil, particularly for row crops. Such non-beneficial depletion, which is the difference between CF and crop ET (Allen *et al*., 1998), would be much less as compared to traditional method of irrigation, more so for row crops. It is possible to achieve the twin-objectives of higher water productivity and higher yield through micro-irrigation. The theoretical 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" would be higher under micro irrigation. 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 (Narayanamoorthy, 2004).[9] This means that even in situations where the entire land is irrigated, farmers might have incentive to go for micro irrigation for such crops. The water productivity gain automatically comes under such situations.

4.2 Improving irrigation water productivity through optimizing input use

In order to assess the potential of "optimum nutrient dosage" in improving crop water productivity, the incremental changes in crop yield and crop water productivity with respect to fertilizer dosage were analyzed. For this, the data collected from four agro-climatic regions in Narmada river basin were analyzed. The analysis included the following: 1] the yield response to fertilizer application; and 2] the water productivity response to fertilizer application.

As regards yield response to fertilizer inputs, in the case of wheat in Hoshangabad, it was found that 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) in 2003, though such trends were not seen for 2002 which was a drought year. Figure 10 shows the response curve of water productivity to fertilizer input across the farmers. Such a response does indicates that farmers are optimally using fertilizers and irrigation water to enhance the returns.

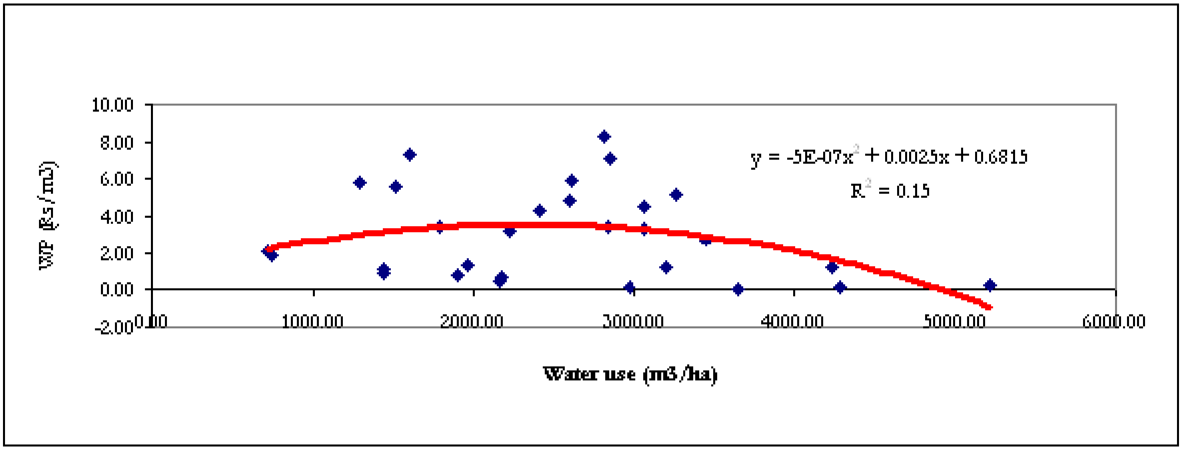
In case of cotton crops in West Nimar, water productivity response curve for fertilizer dosage was "polynomial" for 2002 (drought year) with productivity (Rs./m^3) increasing from the lowest values at low levels of fertilizer use towards the middle range, and then declining (R^2= 0.11). Such a response curve can be explained this way. Very high doses of fertilizers is generally accompanied by 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 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 pet unit of land, and not water.

Figure 8: Water Productivity vs. Irrigation Water Dosage in Cotton in West Nimar- 2003

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

[9]But, cases where farmers are not able to secure optimum levels of water productivity due to water shortages are rare. Well owners have reasonably high degree of control over water delivery. Power supply is the only factor that reduces their water control. In states such as Punjab, Gujarat and Madhya Pradesh, quality of farm power is poor. The supply is provided in rotations, including during night. This might affect the dosage of water farmers could give to crops in hard rock areas with limited groundwater.

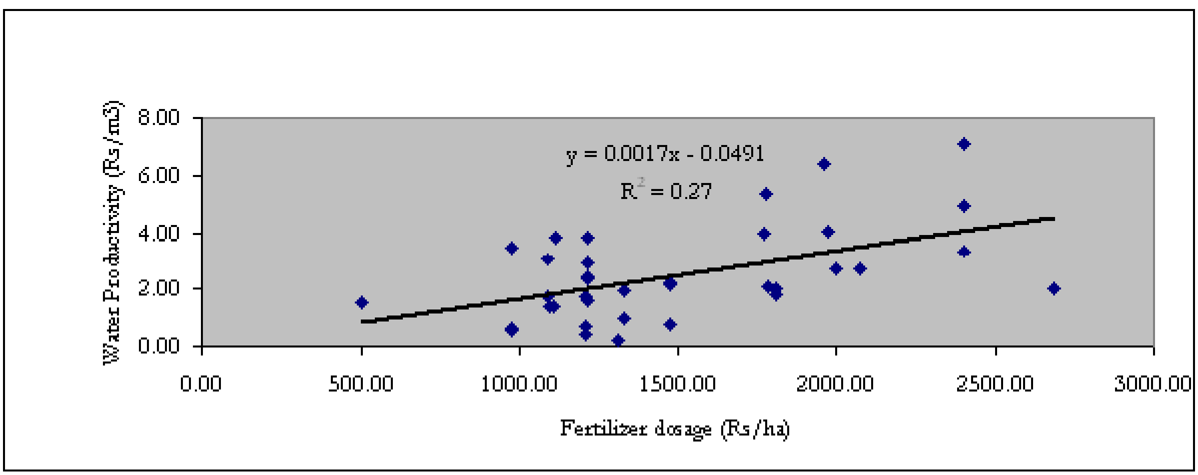
For a "linear response curve" of yield to fertilizer dosage, the response curve for water productivity



(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 2003 (Figure 10). Inverse relationships can occur only if the fertilizer dosage is accompanied by increased dosage of irrigation. With increase in fertilizer dosage, the water productivity could actually rise, and then decline. This is because it would be possible to increase yields with increase in fertilizer dosage, without much change in irrigation dosage up to certain point. Beyond this point, increased use of fertilizer dosage would require greater dosage of irrigation for increasing the nutrient absorption capacity of the plants. This may not result in increase in ET, thereby showing no effect on crop yield. However, this would reduce water productivity as the total depletion or CF would increase. Here adjusting the fertilizer dosage to optimal levels is crucial.

Figure 10: Water Productivity vs. Fertilizer Dosage in Wheat (Hoshangabad 2003)

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, can be enhanced through manipulation of fertilizer use.[10] This might increase water productivity in economic terms as well (as seen in the earlier section). Such situation may be encountered in central India (covering most parts of Narmada, Tapi, Mahi and Krishna basins), where fertilizer use in agriculture is one of the lowest. If fertilizer dosage does not increase the yield, then simple reduction in dosage would result in saving of input costs, thereby

[10]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.

increasing water productivity in rupee terms. Such situations are possible in Punjab and Haryana where application of nitrogenous fertilizer is excessively high.

4.3 Improving water productivity through improving quality & reliability of irrigation water

There is not much empirical evidence to suggest that greater reliability and quality of irrigation leads to greater water productivity.

Analysis from groundwater irrigated areas of north Gujarat showed that the gross returns per cubic metre of applied water was higher for shareholders of tube well companies, when compared to farmers who were buying water from well owners. The gross water productivity was Rs. 5.61/m^3 for tube well owners against Rs. 4.61/m^3 for water buyers. The gross returns only indicate the physical efficiency of water use. It does not take into account the input costs, and only converts the main product and byproduct into cash equivalents. In the case of shareholders, the entitlement of water is fixed in volumetric terms, and water supply is highly reliable. In 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 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 or 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 was that canal irrigators will not be able to apply water at critical stages in right quantities, whereas well irrigators 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 to canal irrigators, the “overall quality of irrigation” would depend on what proportion of the total demand is met from canals, and what proportion from groundwater.

Analysis involved comparing water productivity in wheat under different sources of irrigation in two distinct agro-ecological regions. Adequate numbers of irrigators for each of the three sources of irrigation were 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 was made between conjunctive use and canal water (in sub-mountainous region). The analysis showed that yield figures are lowest for farmers using only canal water for both paddy and wheat; second lowest for farmers using both canal water and groundwater (Table 2). The farmers using well water (in Jalandhar and Kapurthala) got the highest yield. The yield differences between categories within the region and across regions are substantial. 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.

The foregoing analyses clearly show that improvement in quality and reliability of irrigation would impact yield significantly. Here, quality of irrigation includes adequacy and reliability. With greater reliability and adequacy of irrigation, farmers would be able to adopt good agronomic practices and adjust nutrient use. Enhanced quality and reliability of irrigation would also help farmers optimize the irrigation dosages in each watering and give adequate number of watering including watering at critical stages of plant growth. This would not only increase the yield, but also reduce non-beneficial depletion.

Table 2: Differential Land Productivity with varying quality of irrigation in Punjab

Name of Region	Name of District of Irrigation	Predominant Source 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

Whereas with uncertainty in irrigation schedules and water delivery, as found in the case of canal irrigation, farmers hesitate to apply adequate quantities of fertilizers, thereby losing yield. In many cases, the depth of each application is much higher than the optimum dosage determined by the capacity of the field with uncertainty of water supply as compared to assured water supply (well water). This leads to heavy percolation losses and excessive residual moisture after harvest. These cause increase in non-beneficial depletion over crop ET. Greater irrigation dosages may also increase fertilizer leaching, reducing nutrient use efficiency.

4.4 Enhancing irrigation water productivity using climatic advantages

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: page 13), as productivity of applied water is a function of agro-climate (Abdulleev and Molden, 2004). Spatial analysis of water productivity of selected crops was carried out for nine districts falling in seven agro-climatic regions in Narmada basin, and three agro climatic regions in Sabarmati river basin (Table 3 and Table 4). Theoretically, climate can influence both physical productivity of water and water productivity in economic terms. The climate determines the actual consumptive water requirements and potential crop yields, and the availability of soil moisture from precipitation. In regions, with favourable climatic conditions, the biomass output per unit of water evapo-transpired would be higher. 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 highest for Northern hill region of Chhattisgarh in Mandla district (1.80 Kg./m^3) although Raisen falls in the traditional wheat-growing belt; it was lowest for Jabalpur in Central Narmada Valley (0.47 Kg./m^3). This is mainly due to the major difference in irrigation water applied, 127 mm in Mandla against 640 mm in 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 normal year is 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 climatic factors, which changes 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 metre of water was highest for the same region for which physical productivity was higher (Rs. 4.09/m^3). The same was 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 3) 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 3: 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 inEconomic 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

NHRC: Northern Hill Region of Chhattisgarh
Source: authors' own analysis based on primary data

There are only two regions in Narmada basin, which irrigate paddy. The physical productivity for grain during the normal year was higher for Northern hill region of Chhattisgarh in Mandla district (2.13 Kg./m^3) while it was only 1.62 Kg./m^3 in Jabalpur district of Central Narmada Valley. Likewise, water productivity in economic terms was higher for Northern hill region of Chhattisgarh (Rs.3.95/m^3) 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./m3 in Jabalpur.

Similar patterns of variation in water productivity across agro-climates were found in Sabarmati rive basin also. The physical productivity of water 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, and the net water productivity 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, the locations which gave highest economic water productivity did not coincide with that of highest physical productivity of water in case of castor oil.

Synthesis of results on crop water productivity in Narmada basin and Sabarmati basin show that the variation in water productivity of irrigated crops across regions is mainly due to variation in agro-climate, which reduces the crop water requirement. The northern hill 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".[11] 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 of high water productivity-both physical and combined (physical and economic).

5. POTENTIAL FOR IMPROVING IRRIGATION WATER PRODUCTIVITY IN INDIA

5.1 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: 1] the water-intensive crops are grown in these regions; 2] there is poor control over water delivery, and 3] quality and reliability of irrigation is poor. Semi arid and arid regions with deep water table conditions are ideal for water productivity enhancement (reduction in non-beneficial evaporation and non-recoverable deep percolation). Semi arid Punjab and Haryana are known for intensive cropping of wheat and paddy, which have ample scope for improving yield.

After canal irrigated areas, areas that depend on well irrigation and where substantial area is still left uncultivated due to water scarcity should receive attention. The reason is that under such situations, the farmers can expand the area under irrigation and increase aggregate returns. The priority areas would be hard rock areas of peninsular, central and western India. The water-intensive crops grown in large areas in this region are paddy, cotton, sugarcane, banana, cotton, castor, groundnut, and potato (Kumar and Singh, 2006).

Row crops such as cotton, groundnut, potato, castor, banana and sugarcane can also be prioritized for water productivity improvement. Here, it can 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 method 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 serve as successful examples.

5.2 Potential improvements in water productivity and water saving at the basin level

The gain in applied water productivity through "water control" results in same extent of gain in productivity of depleted water only in semi-arid and arid regions where the depth to groundwater table is large,[12] and where non-beneficial evaporation from fallow land is high. In such regions, a significant portion of the applied water depletes. Hence, there can be basin level productivity gains through control over water delivery.[13] However, for farmers to adopt water control measures, they must have extra land to bring under irrigation. This is because the net return per unit area might decline due to water control measures. At the aggregate level, there would be no reduction in the demand for water.

Though micro irrigation would raise crop water productivity both in physical and economic terms without reducing yield (as illustrated by Figure 11). The impact of micro irrigation would be significant in arid and semi arid areas, and for row crops. This is because in case of row crops evaporation component of consumptive use of water by crop (ET) is quite large, especially under aridity conditions (Kumar *et al*., forthcoming). The area under row crops is very small in the sub-humid and humid areas and water abundant areas.

---

[11] See Kumar and Singh (2006) for detailed description of average annual rainfall and reference evapo-transpiration in all the nine agro-climatic regions falling in Narmada basin.

[12] 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.

[13] In other regions—sub-humid and humid regions with shallow groundwater, the basin level water productivity gain would be very much lower.

Peninsular India and Western India have substantial area under crops that are conducive to micro irrigation technologies; north and central India has very little area under such crops with the exception of Uttar Pradesh. Western part of Mahanadi is another area that would be conducive to water saving technologies (WST). Use of micro irrigation system can significantly reduce crop water demand per unit area of cultivated land in semi-arid and arid area, with deep groundwater table conditions or with saline aquifers. However, in these areas, farmers use the saved water to expand the area under irrigation to maximize their aggregate returns (if un-cultivated land is available). As a result, the aggregate demand for water may not change. However, areas where intensity of irrigation is already highest like in central Punjab and Haryana might be exceptions.

The basins that are conducive to measures for improvement in water productivity through water control are: 1] all east-flowing rivers of peninsular India; 2] rivers north of Tapi in Gujarat and Rajasthan; Mahanadi; some parts of Indus basin covering south-western Punjab; and 3] west- flowing rivers of South India. This is because these basins fall under semi arid and arid climatic conditions, and have moderately deep, to deep groundwater levels. These basins have very large areas, which are un-irrigated due to limited availability of groundwater and canal water. Hence, farmers would have incentive to improve water productivity. In the process, they would be able to maximize the aggregate returns.

There are some regions in India where water productivity is not a consideration for individual farmers. The economy here would benefit a lot by reducing the amount of water depleted and the energy used up in growing crops. Such areas include parts of Indus in central Punjab, Haryana and UP, which are groundwater irrigated. In such areas, water productivity improvement measures can help raise income returns from every unit of land irrigated. The only option to enhance water productivity is water delivery control. It can be used effectively in such situations where excessive irrigation leads to yield losses.

In Punjab and Haryana, improving adequacy and reliability 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 departments should have incentive to go for improving both quality and reliability of irrigation water, and “water control”. Since there is no scope for exploding groundwater-irrigated area, it would lead to reduction in groundwater draft as well.

6. POLICY ALTERNATIVES FOR IMPROVING WATER PRODUCTIVITY

It is widely recognized that flat rate mode of pricing of electricity resulted in inefficient, and unsustainable use of groundwater (Kumar and Singh, 2001; Kumar, 2005). Pro-rata pricing of electricity would create direct incentive for efficient water use as it induces positive marginal cost of water application. There will be two different outcomes of this policy change: 1] as the marginal cost of using electricity is positive, farmers would adopt water abstraction systems that are more energy efficient, which means the electricity used for pumping and applying a unit of water would be less, so the marginal cost of increasing the dosage of water; and 2] farmers could increase water use efficiency in crop production, enhancing physical efficiency (Kumar, 2005).

By enhancing water use efficiency, the farmer can reduce the water application to their crops, as the net marginal returns would become negative at original level of water dosage. Such reductions in applied water will be affected without any change in the consumptive use through better farm water management and better conveyance methods. Farmers can also adopt drip irrigation systems that require low energy to run,[14] which also save energy. There would be no adverse effect of reduced irrigation dosage on yield. Instead, the irrigation-net water productivity curve itself would shift diagonally upwards due to slight improvement in net water productivity.

In the long run, total metering and pro-rata pricing would be the most desired scenario, The government can start with metering of agricultural consumption. Heavy subsidy for WSTs can be provided to farmers who are willing to use meters, provided they minimize electricity consumption. It could reduce with increase in total energy consumed, and increase with increase in percentage cropped area under water-saving irrigation technol-

[14] Like micro tubes and sub-surface drip irrigation systems (porous pipes). For details please see Kumar, Singh, Sharma and Amarasinghe (2007).

ogy. This can help realize the twin objective of more efficient and sustainable groundwater use, and efficient energy use.

In groundwater irrigated areas, improving power supply conditions – both quality and hours of supply – is extremely important for achieving greater control over water delivery. Unreliable power supplies and power supply during night time force farmers to apply excess water whenever power supply is available (Kumar and Singh, 2001), instead of application at the critical stages of crop growth that gives higher productivity. This leads to inefficient use from both physical and economic points of view as shown by a study in Mehsana. In canal command areas, farmers should be provided with subsidies for storage systems and small pump sets. This would result in greater control over "water delivery" and better quality of irrigation to achieve higher water productivity in physical and economic terms.

REFEREANCES

Abdulleev, Iskandar and D. Molden (2004), Spatial and temporal variability of water productivity in the Syr Darya Basin, central Asia, Water Resources Research, Vol. 40, W08S02.

Ahmad, M. D., I, Masih and H. Turral (2004), Diagnostic analysis of spatial and temporal variations in crop water productivity: A field scale analysis of the rice-wheat cropping system of Punjab, Pakistan, Journal of Applied Irrigation Science, 39 (10).

Ahmad, M. D., W. G. M. Bastiaanssen and R. A. Feddes (2002), Sustainable Use of Groundwater for Irrigation: A Numerical Analysis of the Subsoil Water Fluxes, Irrigation and Drainage, 51 (3): 227-241.

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

Barker, Randolph, David Dawe and Arlene Inocencio (2003), Economics of Water Productivity in Managing Water for Agriculture, in Jacob Kijne et.al. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement, Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Bastiaanssen, Wim G.M., Mobin-ud-Din Ahmed and Zubair Tahir (2003), Up scaling Water Productivity in Irrigated Agriculture Using Remote-sensing and GIS Technologies, in Jacob Kijne and others (Eds.) Water Productivity in Agriculture: Limits and Opportunities for Improvement, Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Burt, Charles M., Daniel J. Howes, and Andrew Mutziger (2001), Evaporation Estimates for Irrigated Agriculture in California, paper presented at the 2001 Irrigation Association Conference-San Antonio, Texas, November, 4-6.

Choudhury, P. N. and V. Kumar (1980), The Sensitivity of Growth and Yield of Dwarf Wheat to Water Stress at three Growth Stages. *Irrigation Science.* 1: 223-231.

Gichuki, Francis (2004), Managing the externalities of declining dry season river flows: A case study from the Ewaso Ngira North River Basin, Kenya, Water Resources Research, Vol. 40, W08S03.

Hussain et al. (2003), Land and Water Productivity of Wheat in the Western Indo-Gangetic Plain if India and Pakistan: a Comparative Analysis, in Jacob Kijne et.al. (Eds.) Water Productivity in Agriculture: Limits and Opportunities for Improvement, Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Keller, A., J. Keller and D. Seckler (1996), Integrated Water Resources Systems: Theory and Policy Implications, Research Report 3, Colombo: International Water Management Institute.

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

Kijne, Jacob, R. Barker and D. Molden (2003), Improving Water Productivity in Agriculture: Editors' Overview, in Jacob Kijne and others (Eds.) Water Productivity in Agriculture: Limits and Opportunities for Improvement, Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Kumar, M. Dinesh (2007), Groundwater Management in India: Physical, Institutional and Policy Alternatives, New Delhi: Sage Publications.

Kumar, M. Dinesh (2005), Impact of Electricity Prices and Volumetric Water Allocation on Groundwater and Energy Demand Management: Analysis from Western India, Energy Policy, 33 (1): 39-51.

Kumar, M. Dinesh and O. P. Singh. (2001), Market Instruments for Demand Management in the Face of Scarcity and Overuse of Water in Gujarat. Water Policy, 3 (5): 387-403.

Kumar, M. Dinesh and O. P. Singh (2004), Virtual Water in Global Food and Water Policy Making: Is There a Need for Rethinking ?, Water Resources Management, :1-31. (In Press)

Kumar, M. Dinesh and O. P. Singh (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, 16-18 October, 2006.

Molden, David, Hammond Murray-Rust, R. Sakthivadivel and Ian Makin (2003), A Water Productivity Framework for Understanding and Action, in Jacob Kijne et. al. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement, Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Molle, François and Hugh Turral (2004), Demand management in a basin perspective: is the potential for water saving over-estimated, paper prepared for the International Water Demand Management Conference, June 2004, Dead Sea, Jordan.

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

Oweis, T. and A. Hachum (2001), Reducing peak supplemental irrigation demand by extending sowing dates. *Agricultural Water Management* 50: 109-123.

Oweis, T. and A. Hachum (2002), Improving water productivity in the dry areas of West Asia and North Africa. In J.W. Kijne et al. Wallingford (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement, UK: CABI in collaboration with IWMI.

Rockström, J., Jennie Barron and Patrick Fox (2002), Water productivity in rain-fed agriculture: Challenges and opportunities for smallholder farmers in drought-prone tropical ecosystems. In Jacob Kijne and others (Eds.) Water Productivity in Agriculture: Limits and Opportunities for Improvement, Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Saeed, I. A. M. and A. H. El-Nadi (1998), Forage Sorghum Yield and Water Use Efficiency under Variable Irrigation. Irrigation Science 18:67.71.

Seckler, David, D. Molden and R. Sakthivadivel (2003), The Concept of Efficiency in Water Resources Management, in Jacob Kijne and others (Eds.) Water Productivity in Agriculture: Limits and Opportunities for Improvement, Comprehensive Assessment of Water Management in Agriculture. UK: CABI Publishing in Association with International Water Management Institute.

Singh, O. P. (2004), Water Productivity of Milk Production in North Gujarat, Western India, proceedings of the 2nd Conference of the Asia Pacific Association of Hydrology and Water Resources, Singapore, 5-9 July, 2004.

Singh, Tej and D. S. Malik (1983), Effect of Water Stress at Three Growth Stages on the Yield and Water-use Efficiency of Dwarf Wheat, *Irrigation Science* 4:239-243.

Tuong, T. P. and B. A. M. Bouman (2002), Rice Production in Water-scarce Environments. In Kijne, J. W. (Eds.) Water Productivity in Agriculture: Limits and Opportunities for Improvement, Wallingford, UK: CABI (in press).

Xie, Mei, Ulrich Kuffner and Guy Le Moigne (1993), Using Water Efficiently, Technological Options, Technical Paper 205. World Bank, Washington D.C.

Zwart, Sander J. and Wim G. M. Bastiaanssen (2004), Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize, *Agricultural Water Management* 69 (2004): 115-133.