

Water Productivity of Irrigated Agriculture in India: Potential areas for improvement

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The objective of this paper is to estimate water productivity in irrigated agriculture in selected basins in India; and to identify the drivers of change in water productivity in these regions. The analysis considered productivity of applied water. The paper also examined the relationship currently existing in these basins between these drivers and water productivity, and how they need to be manipulated to enhance water productivity. The investigations covered the following potential drivers of change in water productivity: control of irrigation water and input use; climatic variations; and quality of irrigation water supplies. The basins selected are: Indus, Ganges, Sabarmati and Narmada. From Indus, the Bist Doab area and south western Punjab; three agro climatic regions in Sabarmati basin; and seven agro-climatic regions in Narmada basin were selected. Only one agro climatic region from Ganges was selected for the study.

In order to affect the said lines of analysis, relationship between irrigation and fertilizer dosage on water productivity (Rs/m^3) in the same crop across farmers in the same region was studied. Average water productivity figures of the same crop, irrigated from the same type of source under different agro climatic conditions were compared to analyze the impact of climatic variations on crop water productivity. Water productivity in the same crop that is irrigated by sources having different degrees of reliability was compared to understand the impact of quality of irrigation.

The analysis showed the following: a] there are major variations in physical productivity of water across farmers in the same area; b] the same crop grown in different regions has remarkably different levels of physical productivity and economic efficiency; and, c] the same crop has differential water productivity with different qualities of irrigation water applied. Further investigations into spatial variation in water productivity across farmers showed the following trends: 1] most farmers are applying water within a regime where the yield response to both irrigation and fertilizer dosage is positive, showing positive marginal yield with irrigation; and 2] water application and fertilizer dosage regime of farmers corresponds to that part of the water productivity curve where increase in irrigation dosage results in reduction in water productivity, indicating negative “marginal productivity” and inefficient use of water from the point of view of economic efficiency. Nevertheless, in certain situations, farmers’ water application regime coincides with that part of the yield and water productivity curves in which they respond negatively to increase in dosage of irrigation and fertilizers.

The outcomes of the analysis showed that limiting water application through “water delivery control mechanisms” and “micro irrigation systems” can lead to enhancement in water productivity. But the first type of intervention would result in reduced yield due to reduction in consumptive use of water in most situations where the yield response to irrigation was positive. The strategy can work in regions where water is scarce, and where scope exists for expanding the area under cultivation exists. But in situations farmers are applying excessive irrigation leading to yield losses, simple water delivery control would result in both yield and water productivity gains. Further analyses show that improving the quality of irrigation—through intermediate storage systems and reliable power supplies would result in enhanced yield and water productivity. Finally, growing certain crops in regions with low level of aridity and medium to high rainfall would result in higher water productivity for the same crop as compared to that in regions with higher aridity and low rainfalls.

1.0 Introduction

Water use in agriculture is economically far less efficient than in others (Barker *et al.*, 2003; Xie *et al.*, 1993) including the manufacturing sector (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 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 provides a means both to ease water scarcity and to leave more water for other human uses and nature. 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), 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 re use of water is under-estimated (Seckler *et al.*, 2003).

The classical concept of irrigation efficiency used by water engineers to analyze the “productive use” of water omitted economic values and looked at the actual evapo-transpiration (ET) against the total water diverted for crop production (Kijne *et al.*, 2003). Over and above, 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), 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 kilogram of crop per cubic metre of water diverted or depleted (kg/m^3); net or gross present value of the crop produced per cubic metre of water (Rs/m^3) known either as economic efficiency of water use or combined physical and economic productivity of water; and net or gross present value of the crop produced against the value of the water diverted or depleted (Kijne *et al.*, 2003).

Though the major consumptive use of water in many river basins might be in crop production, there would be other competing uses of water, some of which giving higher returns per unit of water consumed or depleted. Therefore, changing inter-sectoral water allocation norms in favour of more efficient uses with proper compensation for the sectors which would help eventually lose part of its due share would result in higher overall basin water productivity. 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 more due to

climatic and agronomic factors (Abdullev and Molden, 2004), indicating the need for inter-regional water allocation.

On the other hand, enhancing water productivity at the field level or irrigation system level through water control may adversely affect the availability of water for downstream uses that have higher return per unit water use, resulting in productivity losses, if the basin is closed. Hence, considerations for enhancing basin level water productivity would be different from that for maximizing the farm level and system level water productivity. The decisions to change water control, water supply, water allocation (intra and inter-regional) regimes to enhance basin water productivity should be based on analysis of: spatial variability in water productivity in the same sector across the basin, water productivity in different competitive and in stream use sectors in the basin and the amount of water available for further use.

In nutshell, if one integrates the “scale consideration” and various physical and economic considerations in water productivity, this means there are many avenues to enhance water productivity in crop production, including yield improvements through better agronomic inputs and obtaining greater water control to reduce the “depleted water”, which enhance physical productivity of water; diverting the available water to economically more efficient crops (that give higher cash return per unit volume of water consumed), and obtaining water control in the same; and finally reducing the amount of applied water which has high opportunity costs.

Great opportunities exist for enhancing productivity of water use in agriculture in India. Some of them include: for a given crop, allocating more irrigation water for crops at the critical stages to meet the evapo-transpirative needs of the plants, which means establishing greater control over timing and quantum of water delivery; 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 it needs to be understood that while the yield would increase with increase in actual ET, the ET corresponding to highest water productivity might be much less than that corresponding to highest crop yield (see for instance Molden *et al.*, 2003). This means there is a clear trade off between yield enhancement and water productivity enhancement. When water becomes scarce, the irrigation water allocation has to be optimized to get positive marginal productivity.

2.0 Objectives of the Study

In this study, the scope for water productivity enhancement is analyzed through estimating: 1] the marginal productivity of water for certain crops with 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.

2.1 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 part of the water productivity response curve to irrigation and nutrient inputs.

2.2 Approach and Methodology

The approach used in the study would be case study based using primary surveys. Four river basins in India would be 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 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 crops, the sample size is 30-35 for each agro climate within a river basin. In addition to that, there would be additional samples for each type of irrigation source. Hence, the total sample size was 90 in the same 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
Ganges	1	1	1 (well + canal)	80
Narmada	9	7	1 (wells only)	450
Sabarmati	6	3	1 (wells only)	180

Productivity of Irrigated Crops

In the case of purely irrigated crops, water productivity would be estimated for both farm-level as:

$$\text{Farm level water productivity of crop } i \text{ and farmer } j = \text{Yield or Net Return } (C_{ij}) / (\Delta_{ij})$$

Using the sample of farmers, with figures of yield and estimated values of irrigation water productivity, regressions would be run to analyze the impact of irrigation and fertilizer inputs on yield and water productivity. The regression model could provide indications on how far water allocation and nutrient inputs are efficient from the point of view of achieving highest water productivity in the existing irrigation and fertilizer and regimes.

Water Productivity across Irrigation Types

Mean values of farm level productivity of applied water in canal irrigation, well irrigation and conjunctive use would be compared for irrigated crops.

3.0 Water productivity in irrigated agriculture in Indian River Basins: Spatial patterns at present

3.1 Complex concepts of water productivity in international parleys

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 provides a means both to ease water scarcity and to leave more water for other human uses and nature. 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), 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 re use of water is under-estimated (Seckler *et al.*, 2003).

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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 kilogram of crop per cubic metre of water diverted or depleted (kg/m^3); net or gross present value of the crop produced per cubic metre of water (Rs/m^3) known either as economic efficiency of water use or combined physical and economic productivity of water; and net or gross present value of the crop produced against the value of the water diverted or depleted. Here value of the water is the opportunity in the highest alternative use (Kijne *et al.*, 2003).

Though the major consumptive use of water in many river basins might be in crop production, there would be other competing uses of water, some of which giving higher returns per unit of water consumed or depleted. Therefore, changing inter-sectoral water allocation norms in favour of more efficient uses with proper compensation for the sectors which would help eventually lose part of its due share would result in higher overall basin water productivity. 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 more due to climatic and agronomic factors (Abdullev and Molden, 2004), indicating the need for inter-regional water allocation.

On the other hand, enhancing water productivity at the field level or irrigation system level through water control may adversely affect the availability of water for downstream uses that have higher return per unit water use, resulting in productivity losses, if the basin is closed.

Hence, considerations for enhancing basin level water productivity would be different from that for maximizing the farm level and system level water productivity. The decisions to change water control, water supply, water allocation (intra and inter-regional) regimes to enhance basin water productivity should be based on analysis of: spatial variability in water productivity in the same sector across the basin, water productivity in different competitive and in stream use sectors in the basin and the amount of water available for further use.

3.2 Water Productivity Assessments in Irrigated Agriculture

Over the past few years, the concept of productivity of water in agriculture has gained ground with a shift in focus from land to water as a factor of production in agriculture owing increasing shortage of water.

The productivity of irrigation is relevant to economists and engineers who are interested in the cost-effectiveness of the investments in water development. Farmers in rain-fed areas, especially in arid areas, are concerned with the capture and effective utilization of the limited rainfall (Kijne *et al.*, 2002). Though the term water use efficiency was first made by Viets (1966) to mean the ratio of crop production to evapo-transpiration (source: Kijne *et al.*, 2002), over the past few years, the concept of productivity of water in agriculture has gained ground with a shift in focus productivity of land owing to increasing shortage of water as a factor of production in agriculture.

Several studies are available from the past which deal with water productivity of crops with respect to evapo-transpiration (ET) of crops (source: Table 1, Kijne *et al.*, 2002: pp8). Musick and Porter (1990) analyzed water productivity for irrigated wheat; Oweis and Hachum (2001) analyzed water productivity of rain-fed wheat. Analyses of Choudhury and Kumar (1980) and Singh and Malik (1983) found 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/m³ against 1.4-1.6 kg/m³ for wet-seeded rice in the Philippines; 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 that light and frequent irrigation give higher water productivity. Rockström *et al.*, (2002) argues that there are no agro-hydrological limits to significantly enhancing rain-fed yield and productivity of green water, and provided evidences from Kenya and Burkina Faso to show that supplementary irrigation enhances water productivity of rain-fed crops (maize and sorghum, respectively) remarkably with greater effect coming with fertilizer management; from Tanzania to show that conservation tillage increases water productivity of maize

Molden *et al.* (2003) provided a basin water accounting framework to help understand the denominator used in water productivity at all scale of interest, such as field, farm, system and basin. The framework recognizes depleted water as the one unavailable for further use in the hydrological system and included water evaporated, flows to sinks and incorporation into products. For treatment of water productivity at the system or basin level, it considers return flows from irrigated fields as fully “available for reuse” unless it is too polluted (see Molden *et al.*, 2003: page 3). Seckler *et al.* (2003), while differentiating between classical irrigation efficiencies neoclassical efficiencies, further expands the term “natural sink” to include two situations: 1] outflows of water from irrigated areas in deserts that subsequently get evaporated; and 2] where severe mismatches between water supply and demand occur in terms of specific time and place (Seckler *et al.*, 2003: page 3).

A study on water productivity of wheat in the canal irrigated areas of western Indo-Gangetic plains in Indian and Pakistan Punjab shows the improvement in water productivity due

to both improvements in farm management practices--crop technology, timeliness of input use, and improvements in water management practices (Hussain *et al.*, 2003). A similar study done by Wim Bastiaanssen and others (2003) in canal command areas of Indus basin in Pakistan shows a positive correlation between yield and water productivity of wheat for both depleted water and diverted water where in they considered evapo transpiration as the depleted water.

Zhu and others (2004) as a part of a water accounting exercise for Huanghe (Yellow) River basin, estimated water productivity (both physical productivity and economic efficiency) for many crops. Among all the three cereals compared, the physical productivity of water was highest for maize (1.40 kg/m³) followed by wheat (0.59 kg/m³) and lowest for rice. The economic efficiency of water was highest for cotton (\$ 0.19/m³), followed by maize (\$ 0.15/m³). They used the total volume of water delivered at the field inlet as the denominator in estimating water productivity functions.

Molle and others (2004) in their study of water use hydrology and water rights in a study of a village in Central Iran emphasizes on how the surface water flows (canals, river flows etc.) and groundwater flows are inter-related when basin move towards “closure”, with storage, conservation, diversion and depletion of water at one point determines what is available at another and therefore the interconnectedness of various users/actors through hydrological cycle (Molle *et al.*, 2004). They argued that well development was tantamount to the reallocation of water from *qanat* owners to well owners; also development of wells reduced groundwater flow for downstream users. Two aspects of the study are crucial from the point of view of analyzing system level water productivity: 1] increasing efficiency of water from surface systems would have adverse effect on groundwater availability when systems are hydraulically inter-connected; and 2] pumping of water from local aquifer can ensure higher reuse of water from canal thereby achieving optimal efficiency of use of surface water.

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. It showed that the deep percolation (recharge) in irrigated fields cannot be estimated using root zone water balance as it will not be same as the return flows from plant root zone. The study quantified the moisture changes in unsaturated soil profile during crop seasons, made the distinction between “process depletion” (transpiration) and evaporation from cropped land. The study found that the vertical water flux in the unsaturated zone is continuous under rice-wheat system with frequent and intensive irrigation.

Kendy and others (2003) carried out a water balance approach to analyze the impact of policy interventions to affect sustainable water use in the semi humid north China plains. They used the difference between irrigation return flow (defined as precipitation + irrigation (I) –ET) and groundwater draft (I) as the net groundwater storage change. In their analysis, the entire return flow was treated as recharge to aquifer system, which made them argue that any intervention to improve the physical efficiency of water use in crop production in the region, which eventually reduces return flow, would fail to make any impact on groundwater. Their analysis treated crop consumptive use (ET) as “water depleted” (Kendy *et al.*, 2003) and did not consider the losses during deep percolation through unsaturated zone.

While it is recognized that the ET values themselves could reduce with irrigation and soil management (Burt *et al.*, 2001), and therefore, improving the chances of cutting down groundwater depletion, the significance of achieving better groundwater balance through reduction in irrigation water application would increase with increasing inefficiency of conveyance of percolating water from the crop root zone to the groundwater system.

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 among others 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, with some of the requirements being 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.

While it is understood that in many developing economies, agricultural water use dominates water use hydrology in river basins, spatial analysis of crop water productivity is an integral element of the tools for solving water management problems in river basins of Asia (Abdullev and Molden, 20004: pp1). Differences in water productivity in river basins are explained in terms of climate and agronomic variations (Saleth, 2005: pp3).

Abdullev 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. Also, it showed that the difference between WP_{supply} and WP_{pet} was smaller in low rainfall years, owing to the fact that farmers' water dosage is close to the crop water requirement. Whereas 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 highest during the dry year, unlike what was found in the case of cotton. The spatial analysis however, failed to look at water productivity variations across regions due to agro climatic factors, and rather looked at variations across farmers and in different years.

The paper by Cai and Rosegrant (2004) deals with the issue of balancing the increasing conflict agricultural and ecological water needs in the Yellow River Basin in China. The study, using the Yellow River component of the large global-level econometric simulation model and a scenario analysis involving options such as water-saving and inter-basin water transfer, analyzed the impact of increasing water withdrawal for agriculture on ecological water needs of the basin. It showed that there is little scope for resolving conflict between agricultural water demand and ecological water demand in the basin if the current water use pattern continued. One of the scenarios generated concluded that by raising basin water use efficiency of 0.67 and then making supplementary water available through inter-basin water transfer could solve the basin's water management problem in the next 25 years.

The study by Gichuki (2004) dealt with the issue of how changes in up-stream land and water use patterns exacerbate the hydrological externality of declining dry season flows and how this effect, in turn, leads to economic externalities on the downstream communities in the Ewaso Ngira Basin in Kenya. The study provided an analytical framework for analyzing the downstream effects of upper land use and water use pattern changes in terms of quantity of stream flows and quality of water. It identified the following major causes of downstream hydrological and ecological changes in Ewaso Ngira basin: 1] changes in land use from natural to planted forests increased runoff by as much as 17% between tree harvesting and establishment of next plantation; 2] runoff is reduced significantly in well managed rain-fed crop land, resulting

in additional percolation, where as in poorly managed land, the runoff rates are higher by an additional 11-36%; 3] degradation of pastureland with loss of grass cover has negative effects on rainfall infiltration; and 4] increasing water withdrawal upstream for irrigation and domestic uses during the dry season had the highest impact on the dry season flows.

A study by Singh *et al.* (2003) estimated salt and water balance at the farm level in Sirsa Irrigation System at Haryana. They used SWAP model, based on Richards' equation for this. The soil hydraulic functions to be used as model parameters in SWAP were estimated, or in other words, the model calibration was done, through an inverse modeling using pedo-transfer functions, with measured values of soil moisture and salt context in the soil for various time intervals. The model was later on validated using another set of measured values of soil moisture in the same fields for a subsequent set of time intervals. The soil water balance (change in soil moisture at a given depth at a given time) and water management response indicators, such as relative transpiration (I), rainfall and irrigation contribution to ET, percolation index, and salt storage index, for paddy-wheat and wheat-cotton systems, were estimated using the validated model.

Singh (2004) analyzed composite farming system in north Gujarat consisting of crops and dairying and estimated productivity of applied water (groundwater) in dairy farming. Kumar, Iyer and Agarwal (2005) analyzed the composite farming system in north Gujarat, to analyze the applied water productivity in dairy production. It also analyzed the farming system to determine the extent to which groundwater use in the region could be reduced without compromising on the farm economy and the milk production through efficient irrigation water use technologies using a simulation model based on linear programming.

3.3 Case studies in different basins to assess water productivity at the farm level

There are several studies done over the past two 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; part of Bhawani basin in Tamil Nadu; and different locations in Sabarmati river basin in Gujarat. The studies included analyses of 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 volume of applied water was used in the denominator of water productivity.

The results of the analyses are presented in a summary form in Table 2 to Table 3 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); cotton (two seasons covering kharif and winter) in Punjab, Gujarat and Madhya Pradesh; kharif paddy in Punjab, UP, Gujarat, Madhya Pradesh and Tamil Nadu.

As Table 1 shows, there are major variations in water productivity across farmers within the same location. This is not only restricted to economic efficiency of water use, but physical productivity of water use also. 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/m³ to 4.27 kg/m³. The economic efficiency of water use ranges from a lowest of Rs.1.35/m³ to a highest of Rs.13.35/m³. Table 2 shows that the applied water productivity in paddy varies across farmers within the same locality from 3.17 kg/m³ to 4.36 kg/m³ in Batinda to 1.21 kg/m³ to 3.96 kg/m³ in Varanasi.

Now, 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 are falling 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 applied water productivity were available for as many as 45 farmers from each location. Hence, comparison of water productivity in wheat would highlight the potential variation in water productivity possible for irrigated crops. The average physical productivity of applied water in wheat ranges from 0.47 kg/m³ in Jhabua to 1.8 kg/m³ in Mandla.

Also highly significant are the water productivity variations across the three river basins, viz., Indus, Ganges and Narmada. This could be the result of variations in water availability situation, agro-climate and the level of agricultural development. First of all, Indus is physically water-scarce river basin; so are Sabarmati and Bhawani, and are all “closed” basins, where in all the surface water resources are diverted for various uses within the basin and are fully depleted, and on the other hand groundwater resources in these basins are also fully utilized. Narmada basin still has unutilized sufficient water resources which are untapped, particularly surface water resources. 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 adoption of crop technologies varies from basin to basin. While Punjab is known for the progressive farmers, and high level of adoption of green revolution technologies and high agricultural productivity, Madhya Pradesh’s agriculture is relatively very backward. 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/m³ in Narmada basin to 2.33 kg/m³ in Batinda, Punjab (Indus) to 2.61 kg/m³ in Banaras, UP (Ganges).

Table 2: Applied Water Productivity in Wheat in three River Basin Locations in India

Name of the basin	Name of the region	Name of the district	Agronomic Efficiency (Kg/m ³)		Net Economic Efficiency (Rs/m ³)	
			Average	Range	Average	Range
Narmada Basin	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
	Northern Hill Region of Chhattisgarh	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 Basin	South-Western Punjab	Batinda	2.33	1.29 – 4.27	5.93	1.25 – 13.35
Ganges Basin	Eastern Uttar Pradesh	Varanasi	2.61	1.65 – 4.98	10.80	5.02 – 24.51
Sabarmati	North Gujarat, Western India	Sabarkantha (Bayad)	2.75		8.9	

		Sabarkantha (H'nagar)	0.80		2.3	
		Ahmedabad	0.71		1.1	
		Kheda	1.71		4.88	

Source: authors' own analysis based on primary data

Table3: Applied Water productivity in Paddy in 3 Selected River Basins in India

Name of the basin	Name of the region	Name of the district	Agronomic Efficiency (Kg/m ³)		Net Economic Efficiency (Rs/m ³)	
			Average	Range	Average	Range
Narmada	Central Narmada Valley	Jabalpur	1.62	0.85 – 2.57	3.95	0.05 – 10.28
	Northern Hill Region of Chhattisgarh	Mandla	2.13	1.20 – 4.00	1.43	0.43 – 7.74
Indus	Punjab		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, Western India	Sabarkantha	0.42		0.91	
		Ahmedabad	1.06		3.34	
		Kheda	0.92		2.98	

Sources: authors' own analysis based on primary data collected from the three basin areas

The variations in physical water productivity across farmers within locations; locations within a basin; and basins results in higher degree of variation in economic efficiency of water use as shown in last columns of Table 2 and Table 3. While the ratio of highest and lowest values of physical productivity is 3.0 in south west Punjab in Indus, the corresponding ratio for economic efficiency is 4.8 for the same location. While the ratio of highest and lowest values of physical productivity is 3.25 in eastern UP, the corresponding value for economic efficiency in the same location is 12.6. The ratio of average physical productivity across basins is 1.45 (3.69/2.54) when south western Punjab and eastern UP are compared; the corresponding ratio for economic efficiency is 2.15 (10.57/4.90).

4.0 Determinants of Water Productivity Variations

The two major determinants of physical productivity of water in irrigated crop production are: the crop out from crop production and the amount of irrigation used. Let us examine the factors which include these key determinants. The crop output is a function of amount of labour used, the amount of irrigation water and the timing of watering which decides the effective water availability in the root zone for meeting the evapo-transpirative requirements, the amount of fertilizers and nutrients available in the crop root zone. While yield respond positively to evapo-transpiration (ET) (Grismer, 2001), which is decided by the amount and timing of irrigation water applied, with resultant enhancement in water productivity, water productivity starts levelling off much before the yield reaches the maximum (see Figure 1 as shown in Molden *et al.*, 2003).

But, increase in fertilizers and nutrients increases the crop yields up to a point, 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 evapo-transpirative 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 comprising reliability and adequacy would affect water productivity, with the same amount of irrigation water applied. 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, labour and irrigation remaining the same.

While labour and fertilizers and nutrient inputs can help enhance the crop yield and physical productivity of water, the economic productivity could reduce, 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, economic efficiency of water use is important for assessing the efficiency with which water is used in crop production.

Water productivity can also be manipulated by manipulating the denominator of water productivity through water control, i.e., by reducing the amount of non-beneficial depletion of applied water in the field, which makes the water supply requirement 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 levelling. We would demonstrate the impact of these factors on changing the key determinants of water productivity and water productivity as such.

4.1 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.

Yield and Water Productivity Responses to Applied Water

In the case of Hoshangabad district, data of applied water, fertilizer dosage, crop yield, and water productivity (estimated) were available for two consecutive years, viz., 2002 and 2003. The regression analysis showed that the relationship between yield and dosage of irrigation water was linear for winter wheat of the year 2002. As shown in Figure 1, wheat yield increased with increase in dosage of water up. It can also be seen that with the same level of irrigation, the yield differences across farmers are quite substantial. This can perhaps be explained by the differential levels of fertilizer use by these farmers.

Figure 2 shows the graphical representation of the variation in yield with differential levels of fertilizer input. It shows a strong direct 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 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.

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 quintals/ha and 31.7 quintals/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 (14.8 quintals/ha and 25 quintals/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 doses of irrigation with proportional increase in fertilizer inputs. By and large, the maximum yield corresponded to maximum irrigation.

As regards water productivity response to applied water, the relationship was inverse and exponential. Higher dosage of water applied meant lower water productivity ($R^2=0.35$). The graphical representation of the two is given in Figure 3. 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/m³), which could be due to the low 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.

Similar analysis was carried out for the same region using data for the year 2003. It showed a positive linear relationship between applied water and crop yield in wheat ($R^2=0.21$). Higher levels of water dosage by and large resulted in higher yield (Figure 4). The incremental yield due to increase in dosage of irrigation water by 100 mm was around 2.3 quintals/ha. The regression between water dosage and water productivity (Rs/m³) showed that a strong inverse relationship between the two like what was found for 2002 (Figure 5). This could be due to the reasons explained above for the same crop grown during 2002. However, some of the farmers who were in the lower range of irrigation dosage (around 200 mm) got very low water productivity values (between Rs.0.09/m³ and Rs.0.71/m³), where as some other farmers got values of approximately Rs.7/m³ 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 as shown by Figure 6 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 apply different dosage of fertilizers and get different levels of yield. For instance, two farmers who applied irrigation dosages of 2518 and 2557 m³ of water to their wheat, applied different levels of fertilizers (worth Rs.1112/ha and Rs. 2400/ha) and in turn got yields of 29.1 quintals/ha and 40 quintals/ha, respectively.

The analysis was repeated for another region, named west Nimar in Narmada basin for cotton of 2002 and 2003. The crop covers two seasons. After the rainy season, the crop is irrigated. The yield response to irrigation was power relationship (Figure 7), with a marginal increase in yield with increase in dosage of irrigation. Many farmers who applied low dosage of irrigation (close to 100 mm) got as much high yields as that obtained by those who applied the highest dose, i.e., 400 mm. The curve showing the water productivity (Rs/m³) response of irrigation dosage (Figure 8) is “inverse and exponential”. The highest water productivity was obtained at the lowest dosage of irrigation, and the lowest obtained for highest dosage.

Interestingly, the yield response to fertilizer dose was found to be nil. The weak response of cotton to irrigation dosage and lack of response to fertilizer dose in the form of yield

fluctuations could be due to the difference in sowing time of farmers across the samples, and the different types of seeds having different yield potential. The sowing time changes the level of effective rainfall available to the crop, which in turn changes the irrigation requirements. In the case of gram in Hoshangabad, the yield response to fertilizer input was extremely weak for both the years.

A third type of yield response to applied water was found in the case of cotton grown in Dhar district in Narmada basin. In this case, the yield response curve was polynomial with yield increasing up to a point, and then declining. The graphical representation of yield variations with changing dose of applied water is given in Figure 9. As Figure 10 shows, the water productivity response to applied water is “inverse, logarithmic”. The yield response curve shows that many farmers are applying water inefficiently from the point of view of land productivity, thereby losing on yield and returns. On the other hand, those farmers who are applying irrigation dosage in excess of 200mm not only get sub-optimal yields, but extremely low water productivity. The reduction in water productivity is faster beyond 200 mm of irrigation has all the parameters that determine water productivity changes unfavourably. While volume of irrigation dosage and input costs increase, the yield reduces.

Yield and Water Productivity Response to Fertilizer Dosage

As regards water productivity response to fertilizer inputs, in the case of wheat in Hoshangabad, it was found that response is extremely weak for the drought year (2002). At the same time, the response was reasonably strong for the normal year 2003. Water productivity was higher for farmers who applied higher dosage of fertilizers ($R^2=0.13$). Figure 11 shows the response curve of water productivity to fertilizer input across the farmers. Such a response does indicate that the farmers are optimally using fertilizers to enhance the returns, with minimum increase in the dosage of irrigation water.

In the case of cotton in West Nimar, water productivity response curve (see Figure 12) was “polynomial” for the drought year (2002), with productivity (Rs/m³ of water) increasing from the lowest values towards the middle range, and then declining ($R^2= 0.13$). Such a response curve could be explained this way. Very high doses of fertilizers could be possible with increased dose of irrigation water. At the same time, no yield gains were obtained due to the same, or the yield gains were nullified by the use of low yielding varieties used by those who used high doses of fertilizers. This makes the productivity curve an ascending one.

4.2 Analyzing the changes in water productivity due to changes in quality

There aren't many empirical evidences available from across the country to provide evidences to the effect that greater reliability of irrigation water supplies and control over water allocation leads to greater water productivity.

Analysis from well 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/m³ of water, against Rs.4.61/m³ for sharecroppers. The gross returns in a way indicate the physical efficiency of water use, as it does not take into account the input costs, and only converts the main product and byproduct 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 sharecroppers, 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 supply². 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. Whereas the farmers who purchase water on hourly basis are at the mercy of the well owners. 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, will not be able to apply water at critical stages in right quantities. On the other hand, farmers using well water, though incur higher cost in terms of capital, would be able to apply water to their crops, as and when they require subject to availability of electricity supply. Where as farmers using both canal water and well water would have higher degree of control over water application over canal irrigators, and the “overall quality of irrigation” would depend on what proportion of the total demand is met from canals, and what proportion from groundwater.

But, analysis involved comparing water productivity in wheat in two distinct agro-ecological regions as adequate samples of irrigators with three different sources of irrigation were not available from the same 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 lowest for farmers using only canal water for both paddy and wheat; second lowest for farmers using both canal water and groundwater (Table 4). The farmers using well water (in Jalandhar and Kapurthala) were found to be getting 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 4: Differential Water 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
Lower Bist Doab	Jalandhar	Well Water	5.2	4.4
Lower Bist Doab	Kapurthala	Well Water	5.98	4.73
Lower Bist Doab	Kapurthala	Well Water	5.52	5.3
Sub Mountainous	Hoshiarpur	Conjunctive Use	4.46	3.82
Sub Mountainous	Hoshiarpur	Conjunctive Use	4.65	3.79
Sub Mountainous	Hoshiarpur	Canal Water	2.77	3.52
Sub Mountainous	Hoshiarpur	Canal Water	3.47	2.8

Source: authors' own analysis using primary data

4.4 Analyzing water productivity variations across regions due to climatic advantages

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 are presented in Table 5 and Table 6 respectively. 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. For both physical productivity and economic efficiency of applied water (generally known as water productivity in case of crop production), 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 evapo-transpired would be higher as in regions with less favourable climate. Here, we have compared water productivity of wheat and paddy which are two significant crops.

In the case of wheat, the physical productivity of applied water for grain production during the normal year was estimated to be highest for Northern region of Chhattisgarh in Mandla district (1.80 kg/m^3) though 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, 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 agronomic efficiency 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 the 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. $4.09/\text{m}^3$), followed by Raisen (Rs. $2.77/\text{m}^3$). But the same was lowest for Narsingpur (Rs. $0.86/\text{m}^3$), which had the second lowest physical productivity.

Table 5: Region-wise Productivity of Applied Water in Narmada River Basin for Selected Crops

Name of the Region	Name of the District	2002-03 (Drought Year)				2003-04 (Normal Year)			
		Agronomic Efficiency (Kg/m ³)		Economic Efficiency (Rs/m ³)		Agronomic Efficiency (Kg/m ³)		Economic Efficiency (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	0.73	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. Northern Hill Region of Chhattisgarh	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. Northern Hill Region of Chhattisgarh	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

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 region of Chhattisgarh in Mandla district (2.13 kg/m^3) where as it was only 1.62 kg/m^3 in Jabalpur district of Central Narmada Valley. Likewise, the economic efficiency of water use was found to be higher for Chhattisgarh (Rs. $3.59/\text{m}^3$) against Rs. $1.43/\text{m}^3$ for Jabalpur in Central Narmada Valley. Similar trend was 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.

Table 5 shows that there is significant variation in physical productivity and economic efficiency (gross and net) of applied water across regions for all the four crops selected from Sabarmati river basin.

Table 6: Region-wise Productivity of Applied Water for different crops in Sabarmati River Basin

District	Taluka	Agronomic Efficiency main product (Kg/m^3)	Economic Efficiency Gross	Net Return (Rs/m^3)
Wheat				
1.Ahmedabad	Daskroi	0.71	4.66	1.38
2.Kheda	Kapadwanj	1.71	12.37	4.88
	Petlad			
3.Sabarkantha	Himmatnagar	0.79	6.17	2.35
	Bayad	2.75	18.39	8.96
Bajra				
1.Ahmedabad	Daskroi			
2.Kheda	Kapadwanj	1.23	8.17	12.13
	Petlad	0.73	4.09	1.91
3.Sabarkantha	Himmatnagar	1.08	6.92	3.67
	Bayad	3.22	19.07	9.53
Paddy				
1.Ahmedabad	Daskroi	0.53	8.80	3.34
2.Kheda	Kapadwanj			

	Petlad	0.92	6.04	2.98
3.Sabarkantha	Himmatnagar	0.42	2.90	0.91
	Bayad			
Castor Oil				
1.Ahmedabad	Daskroi			
2.Kheda	Kapadwanj	1.62	23.42	14.32
	Petlad			
3.Sabarkantha	Himmatnagar	0.66	9.69	3.56
	Bayad	1.60	25.57	16.40

Source: authors' own analysis based on primary data

5.0 How to enhance Water Productivity in Irrigated Crops?

5.1 Improving Control over water delivery 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] Farmer are not able to make correct judgment about water allocation for maximizing the aggregate returns--which is the multiple of water productivity and total quantum of water applied in the entire irrigated crop--, due to lack of correct information about the levels of irrigation that yield maximum water productivity; or
- 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 highest water productivity¹. What “water control” interventions or interventions that help establish greater control over water delivery, would actually help enhance water productivity and to what extent it would enhance it 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 dosage. But the major sources of non-beneficial depletion are: a] the deep percolation, which is either lost in vadose zone, or which joins the saline aquifer; or b] the evaporation of soil moisture after crop harvest during the fallow period.

¹ It is also be to be noted that water productivity is not a objective for farmers to realize when water is in plenty. On the contrary, they would try and maximize the returns per unit of land, for which yield enhancement is the best route.

We have seen three different types of responses of yield and water productivity to irrigation dosage. We would 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 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. Then, it is likely that with increase in dosage of irrigation, the physical productivity of water also might increase slightly. But, the water productivity response to applied water is “inverse-logarithmic”. Here, the best strategy for most of the farmers would be to minimize the irrigation dosage and proportionally reduce fertilizer dosage, which would help obtain highest water productivity in economic terms. This is the most ideal situation for enhancing water productivity and aggregate return, as there is no need to even expand the area under irrigation to enhance the net returns. Here some of the farmers could but enhance the aggregate (net) return by reducing intensity of irrigation, while some others would enhance the aggregate return by increasing intensity of 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. This is the situation found in the case of irrigated cotton in Dhar district (based on Figure 11). 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 “inverse-logarithmic”. This is the most ideal situation where those farmers who are loosing on the yield and income returns have an incentive to reduce irrigation dosage, by which they could enhance both yield and water productivity. 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.

There are many water allocation and control measures. Water control is possible either through two methods: 1] micro irrigation technologies; 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] improves control over applied water; and b] reduces 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 improving control over applied water, by limiting the dosage each time. This, in a way, also may help reduce non-beneficial depletion but its impact may be less significant as compared to 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 is the only factor that reduces the control over water delivery. In states such as Punjab, Gujarat and Madhya Pradesh, 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 crop yield is the consumptive use of water by the crop (ET) and the how far the transpirative requirements of the crop area met during critical stages of crop growth. Using micro irrigation, the non-beneficial depletion of applied water could be reduced to nil. Such non-beneficial depletion 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 and water productivity to irrigation dosage under traditional irrigation and micro irrigation is given in Figure 13. It shows that the yield corresponding to the same amount of “applied water dosage” would be higher under micro irrigation. This means that even in situations, where the entire land is irrigated, farmers might have incentive to go for micro irrigation. The water productivity gain automatically comes under such situations.

5.2 Changes in input use and potential impacts on water productivity

We have provided evidences to the effect that besides irrigation, fertilizer inputs also impacts on crop yields. This is illustrated by the positive linear relationship between fertilizer dosage and crop yield for wheat in Hoshangabad. Though such relationships could exist due to the added effect of irrigation which follows additional use of fertilizers, closer look at the yield, irrigation and fertilizer use for selected samples’ data highlights the effect of fertilizer. In the case of cotton and gram, the response curve of yield to fertilizer dosage was not sharp enough. This does not mean that fertilizer dosage does not impact on crop yield. It only means that under the fertilizer application regime followed by the sample farmers, the response curve is flat, indicating heavy dosage of fertilizers.

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 logarithmic); but could be polynomial or “direct and linear”. Inverse relationships can occur only if the fertilizer dosage is accompanied by increased dosage of irrigation. In the first case (“polynomial”), up to a point, with increase in fertilizer dosage, the water productivity could actually rise, and then decline. This is because of the higher yield, which increases the value of the numerator of water productivity; where as the denominator may not change. 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 (scientifically correct) dosage of fertilizers. This means that the physical productivity (kg/m^3) of water could be enhanced through manipulation of fertilizer use, as the denominator of water productivity does not change with change in fertilizer dosage. But, primary data collected from farmers 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.

5.3 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. 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.

For 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 to 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 harvest as well, which gets depleted in soil evaporation. Greater dosages also increase the changes of fertilizer leaching, which leads to reduced nutrient use efficiency. Improving the quality of irrigation in such would help farmers optimize the irrigation dosages in each watering and give adequate number of watering with the same volume. This would not only increase the yield, but also reduce the wastages in irrigation, thereby enhancing water productivity of not only applied water, but also depleted water.

5.4 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 from region to region. The physical productivity figures are far below the normal figures for wheat in many regions. It was found to be highest in the northern hill region of Mandla (Rs.1.8 kg/m³), and lowest in Jabalpur (0.47 kg/m³) during a normal year. This difference could be attributed to the difference in agro climate across regions, which reduces the denominator of water productivity function, 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/m³, 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 favourable 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 agronomic and economic efficiency.

6.0 Potential Crops/Areas in India for Improving Irrigated Water Productivity

6.1 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 control"; and 3] poor quality of irrigation. It is a general notion that productivity is generally high in regions such as Punjab and Haryana, which receive extensive and intensive canal irrigation. These regions are also known for intensive cropping of wheat and paddy. Our analysis has shown that there is ample scope for improving water productivity

through improving the quality of irrigation--adequacy and reliability in wheat and paddy. Hence, water productivity improvement should focus on these areas and the two crops mentioned above.

After canal irrigated areas, areas which depend on groundwater for irrigation and where substantial area is still left un-cultivated during winter and summer seasons due to water scarcity should receive attention for water productivity enhancements, as it makes economic sense. 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, ground nut, 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, ground nut, potato. In crops such as paddy, water productivity enhancement has to come through "water control" and "improving the quality of irrigation". In case of crops such as cotton, ground nut, potato, castor, banana and sugarcane, it can also come from the use of micro irrigation devices. Enhancement in water productivity through micro irrigation devices would be much higher than that through water control. 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".

6.2 Basin level potential for improvements in water productivity

We have seen that there is ample scope for raising 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 same extent of gain in productivity of depleted water only in semi-arid and arid regions where the depth to groundwater table is large², and where non-beneficial evaporation from fallow is high. Hence, only in such regions where all the applied water or a significant portion of the applied water is depleted, there would be basin level productivity gains through control over water delivery. In other regions--sub-humid and humid regions with shallow groundwater, the basin level water productivity gain would be very slightly lower. This is because at higher doses of water applied, the return flows would be higher, and at lower levels of irrigation dosage, the return flows would be insignificant.

Though micro irrigation would raise water productivity without reducing yield (as illustrated by Figure 13), the impact of micro irrigation again would be significant in arid and semi arid areas, and in areas where row crops are grown. 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 water-saving irrigation technologies; north and central India has very little area under such crops with the exception of Uttar Pradesh. Uttar Pradesh accounts for nearly 25 % 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,

² 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.

with the resultant increase in basin level water productivity being meager. Western part of Mahanadi is another area that would be conducive to WSTs.

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. This is because these basins are falling 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 as, in the process, they would be able to maximize the aggregate returns. The basins that are not conducive to water control measures are Ganga, Brahmaputra and Meghna.

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. In these basin 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, eastern UP and Bihar. In these areas, water availability is not a constraint in maximizing farm returns, but land availability is. But, at least in some of these basins, including parts of Ganges in Bihar, eastern UP, Assam, the crop yields are currently very 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.

6.3 Implications of water productivity change on water demand and supply 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, and least implications for actual water demand per unit of cultivated area in sub-humid and humid areas. But, in semi arid and arid areas, the farmers would expand the area under irrigation to maximize their aggregate returns in the presence of sufficient un-cultivated land, and as a result the aggregate demand for water may not change. Exceptions would be those where farmers water their crops in excess of the crop requirement, which leads to yield losses.

On the other hand, “water delivery control” would reduce the consumptive water use by the crops per unit irrigated area irrespective of the agro-climate. But, the reduction in the total water depleted through water control measures would be less than the reduction in applied water dosage in sub-humid and humid and cold climates with shallow groundwater conditions. This is because, with increase in dosage of water under traditional method 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.

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.

Reduction in applied water to enhance water productivity would not result in significant reduction in return flows in river basins which are water-scarce. This is because a major chunk of the water in excess of the consumptive water demand would eventually get evaporated from the soil moisture zone during fallow period.

7.0 Institutional and Policy Alternatives for Improving Water Productivity

Pro-rata pricing of electricity would create direct incentive for efficient water use as it induces positive marginal cost of water application (Kumar, 2005). This can bring about two changes in the way farmers use water and electricity. *First:* 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, and therefore the marginal cost of increasing the dosage of water. *Second:* farmers could increase the efficiency of use of water in crop production itself reducing the wastages from the point of view of physical efficiency.

By doing this the farmer would pull back the marginal return (per unit of land) curve horizontally. In a practical sense this means that though the net marginal returns would become zero at lower level of water application, the aggregate return may be higher or would not get affected. Such reductions in applied water (without changing the consumptive use) can be achieved through better on farm water management, better conveyance methods etc. Farmers can also adopt non-pressurized drip irrigation systems, which save not only applied water but also energy. This does not mean that those farmers whose irrigation dosage is in the descending part of the irrigation-water productivity response curve limit their dosages significantly. There would be no major shift in the relative positions of farmer in the irrigation-water productivity curve. It only means that the irrigation-net water productivity curve itself would shift diagonally, due to which there would be slight improvement in net water productivity across farmers.

But, many states are facing serious problems in introducing metering of agricultural pumps and recovering consumption based charges for power use. While in the long, total metering and consumption-based pricing would be the most desired scenario to emerge, the government can start with metering of agricultural consumption. Cash incentives or heavy subsidy for WSTs could be provided to farmers who are willing to use them, subject to them minimizing the consumption of electricity. It could be an inverse function of the connected load or the average energy consumed and the area under water-saving irrigation technology.

In well command areas, improving power supply conditions--both quality of power and hours of supply--, is extremely important for achieving greater control over water delivery. Unreliable power supplies and power supply during nights encourage farmers to apply excess water whenever supply is on (Kumar and Patel, 1995), instead of applying water at critical stages of crop growth that give higher productivity even in areas when water supply is extremely limited. This leads to inefficient use from both physical and economic points of view³. A study

³ While one could argue that the positive yield response to irrigation reflects increase in consumptive use of water by the crop, and therefore reducing water application may not make sense from the point of view of obtaining securing high yields, it is important to note that irrigation dosage explains yield increase only to a limited extent. There are many other factors that govern crop yield. The very fact that for the same irrigation and fertilizer dosage, different farmers get different yield levels itself means that the timing of irrigation also would matter in securing yields.

in Mehsana showed significant yield differences between farmers who irrigate using diesel pumps and those who irrigate using electric pumps mainly owing to the difference in degree of control over water delivery. In the case of diesel well commands, the yields and net returns were much higher irrespective of the high cost of irrigation in case of diesel well owners (Kumar and Patel, 1995).

In canal command areas, farmers are provided with subsidies for storage systems and small pump sets. With such facilities, the physical constraints that exist for adoption of water-saving irrigation technologies can also be overcome. This would result in greater control over “water delivery” and better quality of irrigation to achieve higher physical efficiency and water productivity.

Improving the administration of subsidies is also of paramount importance. Though have been in existence for the past several years, the welfare impacts have been negligible. Alternatively, the farmers should be made to pay the full cost of the system initially, and subsidies could be released in installments based on periodic review of performance of the system in the farm. The manufacturers should sell the system at the market price instead of subsidized price, which would compel them to improve the competitiveness of their products in the market. This would also compel them to provide good technical input services so as to sustain the demand.

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Figure 1: Water Use Vs Yield (Wheat 2003) in Hoshangabad

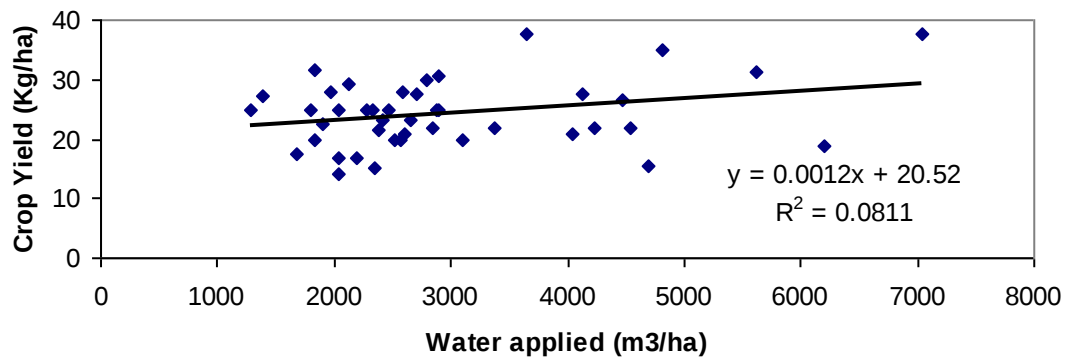


Figure 2: Fertilizer Use Vs Crop Yield in Wheat (2002) in Hoshangabad

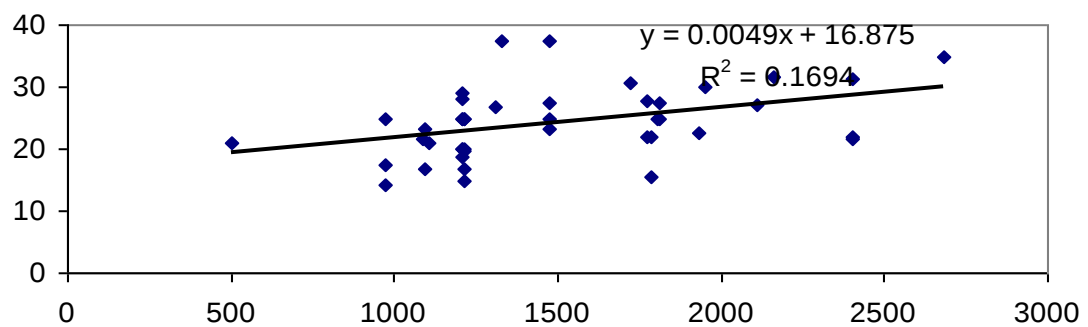


Figure 3: Water Use vs Water Productivity in Wheat (2002)

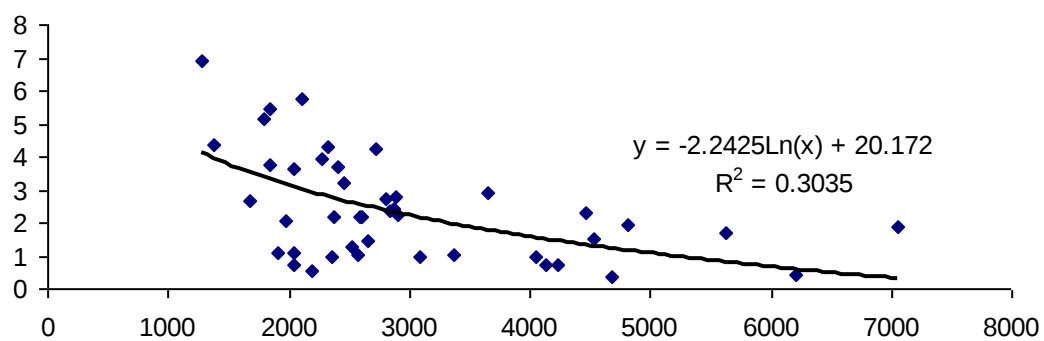


Figure 4: Water Use Vs Crop Yield in Wheat (2003) in Hoshangabad

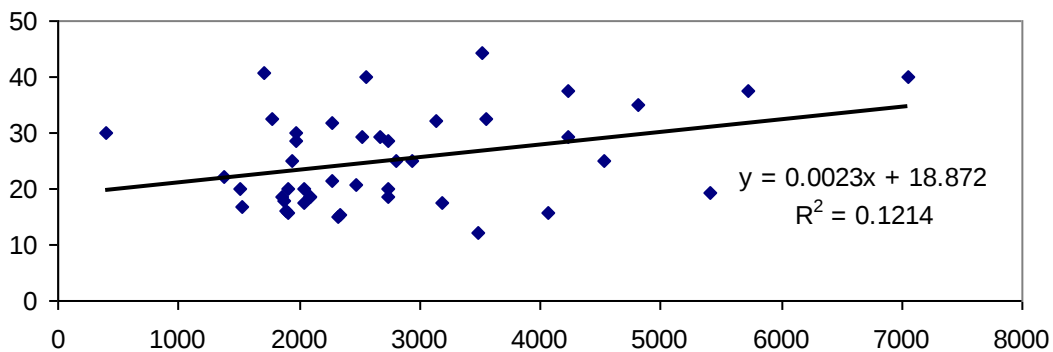


Figure 5: Fertilizer dose vs Crop Yield in Wheat (2003)

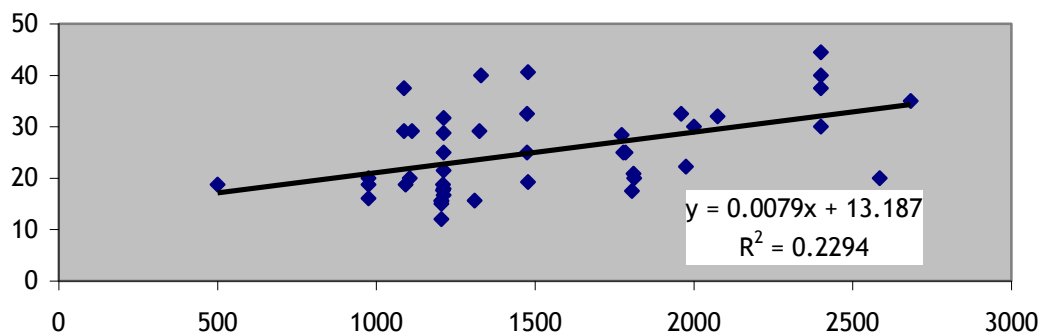


Figure 6: Water Use vs Water Productivity in Wheat (2003)

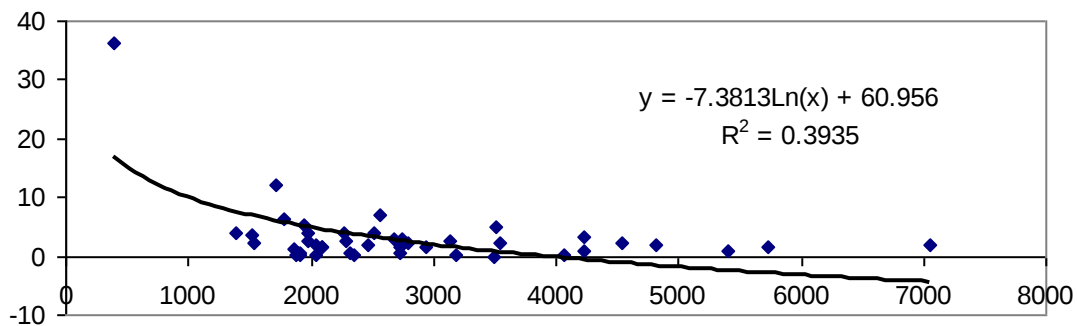


Figure 7: Water Use Vs Yield in Cotton in West Nimar (2002)

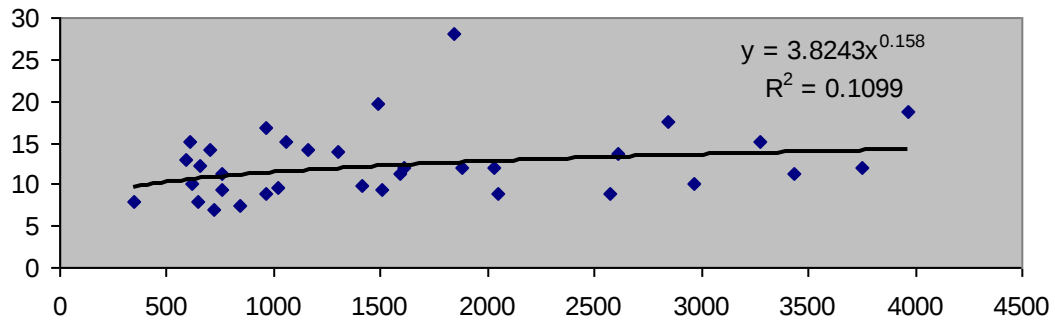


Figure 8: Water Use vs Water Productivity in Cotton (2002)

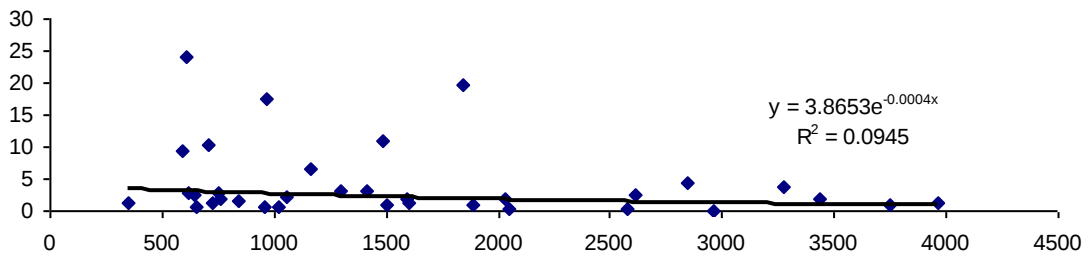
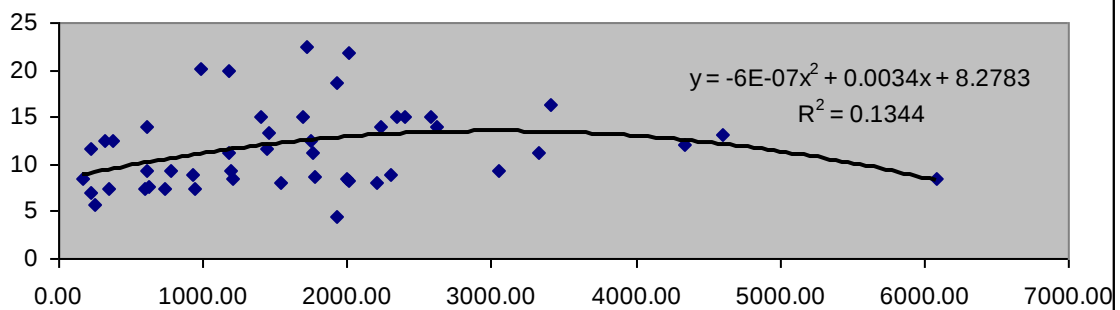
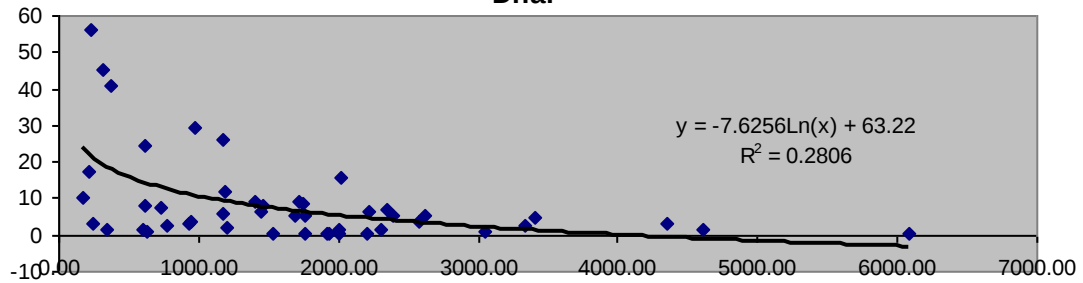


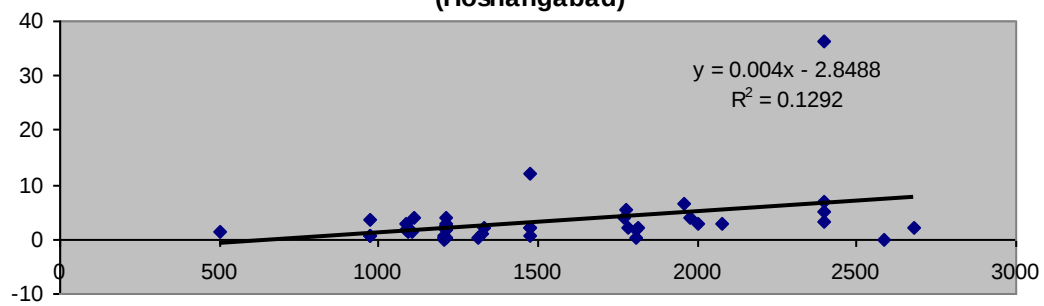
Figure 9: Water Use vs Yield in Cotton (2003), Dhar



**Figure 10: Water Use vs Water Productivity in Cotton (2003),
Dhar**



**Figure 11: Fertilizer Use and Water Productivity in Wheat
(Hoshangabad)**



**Figure 12: Fertilizer Use and Water Productivity in Cotton (2002),
West Nimar**

