Analysis of cotton water productivity in Fergana Valley of Central Asia

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ABSTRACT

Cotton water productivity was studied in Fergana Valley of Central Asia during the years of 2009, 2010 and 2011. Data was collected from 18 demonstration fields (13 in Uzbekistan, 5 in Tajikistan). The demonstration field farmers implemented several improved agronomic and irrigation water management practices. The average values of crop yield, estimated crop consumptive use (ET_a) and total water applied (TWA) for the demonstration sites were, respectively, 3700 kg/ha, 6360 m^3/ha, and 8120 m^3/ha. The range of values for TWA and ET_a were, respectively, 5000 m^3/ha to 12,000 m^3/ha and 4500 m^3/ha to 8000 m^3/ha. A quadratic relationship was found between TWA and ET_a. The average yield of the adjacent fields was 3300 kg/ha, whereas the average yield of cotton in Fergana Valley as a whole was 2900 kg/ha, indicating 28% and 14% increase in crop yield, respectively, from, demonstration fields and adjacent fields. There was no significant difference in crop yields between the wet years (2009 and 2010) and the dry year (2011), which is explained by the quadratic relationship between TWA and ET_a. The water productivity values ranged from 0.35 kg/m^3 to 0.89 kg/m^3, indicating a significant potential for improving water productivity through agronomic and irrigation management interventions. The ratio of average ET_a divided by average TWA gave an average application efficiency of 78% (some fields under-irrigated and some fields over-irrigated), the remaining 22% of water applied leaving the field. Since more than 60% of the water used for irrigation in Tajikistan and Uzbekistan is pumped from, even if all this 22% of water returns to the stream, substantial energy savings would accrue from improving the average application efficiency at field level. The range of values for TWA indicates the inequity in water distribution/accessibility. Addressing this inequity would also increase water productivity at field and project level.

Keywords: Furrow Irrigation of Cotton; Irrigation in Fergana Valley; Water Productivity

1. INTRODUCTION

After independence from the former Soviet Union (in 1991), the operation and maintenance of irrigation and drainage systems was neglected due to lack of adequate financial resources. This exacerbated the pre-existing problem of waterlogging and salinity of irrigated lands. In Central Asia as a whole, more than 5.97 million ha of irrigated area out of the total irrigated area of 8 million hectares requires artificial drainage. There were significant investments in drainage in the region until 1990s. However, with the collapse of the Soviet Union, drainage systems are no longer properly maintained and the area under waterlogging and salinity has been steadily increasing: 35% increase in waterlogged area and 62% increase in area under moderate to high salinity [1].

Furthermore, the State/Collective farms disintegrated, with nobody to claim the ownership of irrigation and drainage infrastructure. Land was distributed to local people, irrespective of their prior background in agriculture. In Kyrgyzstan, Kazakhstan and Tajikistan, farmers own their land, whereas in Turkmenistan and Uzbekistan farmers lease their land from the government. Disintegration of large farms has increased the number of farmers the majority of whom have inadequate knowledge/skills of irrigated agriculture. There was insufficient on-farm irrigation infrastructure to distribute water to individual farmers. During the Soviet era, every State/Collective farm had professional agronomists and irrigation specialists for providing advisory services for irrigated agriculture. However, with the collapse of the system, some of this expertise was lost. Without adequate irrigation infrastructure and organizational support for water distribution below the tertiary canal level, irrigated agri-

culture became chaotic-head-end/tail-end problems, inequity and unreliability in water supply, lack of advisory services on agricultural practices, lack of appropriate farm machinery for operation on small farms, etc.

After year 2000, through Agricultural Reform Acts, Water Users Associations (WUAs) have been formed. This process is not complete in Tajikistan and Turkmenistan. The Government agencies provide bulk water supply to WUAs, and then it is the responsibility of WUAs to supply this water equitably to individual farmers. Yet, there are problems of equity and unreliability of water supply within WUAs hindering improved water management at plot level. This situation combined with waterlogging and salinity has resulted in significant reductions in crop yields.

With a view to increase crop yields from irrigated agriculture, the Swiss Agency for Development and Cooperation (SDC) financed a project for improving water productivity at plot level (WPI-PL). The project had two objectives. The first objective of the project was to develop and evaluate an effective mechanism called "Innovation Cycle" for dissemination of knowledge on improving water productivity to farmers in the Fergana Valley of Central Asia on an experimental basis. This objective was accomplished successfully during the three year period of the project. A separate paper is being prepared on the structure and functioning of the developed Innovation Cycle. The second objective of the project was to evaluate the effect of the Innovation Cycle on improving water productivity of agricultural crops in Fergana Valley. To this end, data on irrigated agricultural production of several major crops such as cotton and wheat, and other crops such as potato, maize, sunflower, watermelons, cucumbers, onions, etc., were collected from several demonstration sites in the countries of Kyrgyzstan, Tajikistan and Uzbekistan. In the past, some general studies were undertaken on water productivity of major crops (cotton and rice) in Syr Darya basin [2,3].

However, no water productivity studies were conducted at field level after implementing the Agricultural Reform Acts of early 2000's. In addition, no data are available on water productivity of agricultural crops under improved agronomic and irrigation water management practices because no effective mechanisms for dissemination of irrigated agriculture knowledge exist in Central Asia today. This paper discusses cotton water productivity from demonstration fields in Tajikistan and Uzbekistan that received irrigated agriculture advisory services from the WPI-PL project.

2. DESCRIPTION OF SITE

To assess cotton water productivity at field level, dem-

onstration sites were selected in Fergana Valley of Central Asia. Fergana Valley is located in the Southeastern part of Central Asia region and the Eastern part of Aral Sea basin, and its territory is shared by three countries—Kyrgyzstan, Tajikistan and Uzbekistan. The Fergana Valley forms the upper and mid-reach of the Syr Darya Basin. Syr Darya is formed from the confluence of Naryn and Karadarya rivers. The average temperature in the Valley is 13.1˚C, ranging from −8˚C to 3˚C in January and from 17˚C to 36˚C in July. Annual precipitation varies from 109 mm to 502 mm, whereas evaporation ranges from 1133 mm to 1294 mm throughout Fergana Valley. Fergana Valley is home for 11,342,000 people over an area of 124,200 km^2.

Data on water productivity were collected from a total of 23 demonstration sites—13 sites in Uzbekistan, 5 sites in Kyrgyzstan, and 5 sites in Tajikistan. The main criterion used in the selection of demonstration sites was that the farmer must be a "progressive farmer", *i.e.* a farmer with background in irrigated agriculture and was willing to experiment with innovative agronomic and irrigation practices. All the selected demonstration site farmers in Kyrgyzstan did not grow cotton. Therefore, data only from the remaining 18 sites was used to calculate water productivity of cotton. The location of these 18 sites is presented in **Figure 1**. At each of these 18 demonstration farms, an adjacent farm was also selected for comparison purposes.

For all the 18 demonstration fields, information on soil texture, soil-moisture content at field capacity, and depth of watertable from ground surface was collected (**Table 1**). Soil salinity is not an issue at most of the demonstration sites. All the fields practiced furrow irrigation, with runoff from the downstream-end of the fields. The fields are sloping with undulations. No data was collected on the degree of undulations in each field. Flow measurement structures were installed at all the demonstration sites to measure the amount of irrigation water applied to the fields and the amount of runoff from the fields. Information on the irrigation norms (based upon hydromodule zoning) was also provided to relevant WUAs. In Uzbekistan, cotton crop is mandated to be grown in order to meet the annual production quota that is determined by the government. In order to facilitate the meeting of total national quota, a target yield level is set for each field based upon the soil-texture, soil fertility, condition of watertable, level of soil salinity and salinity of water used for irrigation. In addition, farmers are provided with credit facilities for acquiring the necessary agricultural inputs. Farmers are required to produce cotton yields that are at least equal to the target level set by the government. If any farmer fails to meet the production target, his/her land lease will be re-negotiated. Furthermore, the farmers are expected to sell cotton only to the government. Cot-
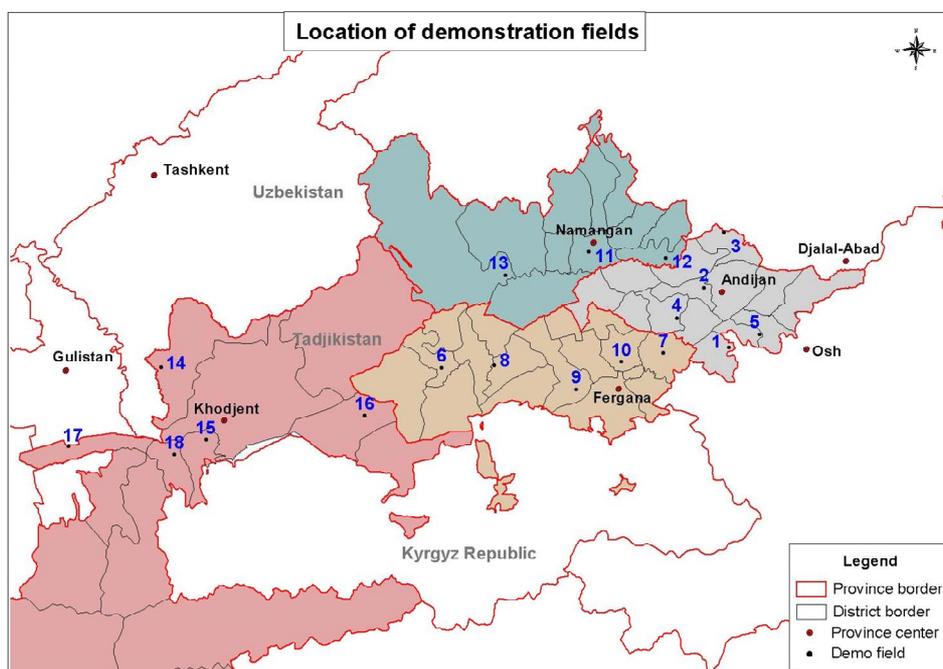
Figure 1. Location of demonstration sites in Tajikistan and Uzbekistan.

Table 1. Field capacity and depth to watertable of demonstration sites in Tajikistan and Uzbekistan.

Province	Site №	Field capacity, mm/m	Depth to Watertable, cm
Andijon	1	177	>300
	2	181	150
	3	184	>300
	4	167	200
	5	189	>300
Fergana	6	192	160
	7	173	160
	8	166	150
	9	139	140
	10	125	250
Namangan	11	150	>300
	12	184	150
	13	192	>300
Sogd	14	167	>300
	15	192	>300
	16	167	>300
	17	125	>300
	18	192	>300

ton is not a mandated crop in Tajikistan; therefore, no government financed credit facilities are provided to farmers. Though the farmers in Tajikistan have the incentive to produce high yields of cotton, lack of credit may be a constraint for increasing agricultural production per unit area. In addition, farmers' income is also vulnerable to the world market prices.

All the demonstration site farmers received information on a set of innovative agronomic and irrigation practices to improve water productivity at field level (**Table 2**). These innovative practices included: land preparation, agro-ameliorative certification of farms, proper sizing of irrigation schemes, mixing of mineral fertilizers with organic fertilizers (manure), application of liquid mineral fertilizers through irrigation water in furrows, adoption of volumetric water delivery method, irrigation scheduleing, measurement of irrigation flow using Sokolok method, short furrow irrigation, alternate furrow irrigation, installation of plastic films at the head of furrows, runoff recovery, cutback irrigation, water rotation, inter-row cultivation, and leaching of salts. As shown in **Table 2**, most of these recommendations were implemented by several demonstration field farmers. Almost all the farmers used alternate furrow irrigation, short furrow irrigation, good pest control measures, inter-row cultivation, and re-use of runoff water from fields.

In order to calculate the net benefits accrued to the demonstration farm farmers, the following information was collected: type and kilogram of seed farmer applied per hectare, amount and cost of fertilizer and pesticides used per hectare, cost of equipment for tillage and culti-

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Table 2. Technologies used at demonstration sites.

Site №	Agro technical activities and land preparation for irrigation season	Leveling of irrigated land	Agro-ameliorative certification of farms	Selecting technological irrigation scheme	Application of mineral fertilizers (soil fertility improvement) for cotton and other crops in conditions of Fergana Valley (to irrigate through pits filled with organic fertilizers)	Fertilizer irrigation through application of liquid mineral fertilizers with irrigation water (fertigation)	Crop pest control	Water accounting (construction of water measuring devices, implementation of water accounting) is organized on inlets and outlets	Adoption of volumetric water delivery method (payment per m^3 of water received). Preparation of necessary documents (contract between WUA and farmer, water accounting log, act, etc)	Implementation of crop irrigation regime	Irrigation considering soil moisture	Mechanism of efficient irrigation water use in small farms (Sokolok)	Defining needs and problems of farmers hindering land and water productivity improvement	Short furrows	Every second furrow irrigation	Variable jet furrow irrigation	Night irrigation	Installation of plastic films in the furrow heads	Use of plastic bottle heads and siphons	Decrease of technological discharges from the fields (use of drainage water or secondary use of water on downstream fields)	Water rotation	Inter-row cultivation	Leaching of saline soils with different types of salinity
										2009													
1	1			1	1	1	1	1		1		1	1	1	1		1	1		1	1	1	
2	1			1	1	1	1	1		1		1			1		1	1			1	1	
3	1			1	1	1	1	1		1		1	1	1	1		1	1		1	1	1	
4	1			1	1	1	1	1		1		1			1		1	1			1	1	
5	1			1	1	1	1	1		1		1	1	1	1		1	1					
6	1	1			1		1	1		1		1	1	1	1		1	1		1			1
7	1	1		1	1	1	1	1		1		1			1		1	1		1	1	1	
8	1			1	1		1	1		1		1								1			1
9	1	1	1		1	1	1	1		1	1	1	1	1	1		1	1		1	1	1	
10	1	1		1	1		1	1		1	1	1	1	1	1		1	1		1			1
11	1				1		1			1		1	1	1	1		1	1		1	1	1	
12	1				1		1			1		1	1	1	1		1	1		1			1
13	1			1	1	1	1					1	1	1	1		1	1					
14	1	1	1	1		1	1		1	1		1			1	1	1	1		1	1	1	
15	1	1	1	1		1	1		1	1		1			1	1	1	1		1	1	1	
16	1	1	1	1		1	1		1	1		1			1	1	1	1		1	1	1	
17	1	1	1	1		1	1		1	1		1			1	1	1	1		1	1	1	
18	1	1	1	1		1	1		1	1		1			1	1	1	1		1	1	1	
										2010													
1	1			1	1	1	1	1		1		1	1	1	1		1	1		1	1	1	
2	1			1	1	1	1	1		1		1	1	1			1	1			1		
3	1			1	1	1	1	1		1	1	1	1	1			1	1	1	1	1	1	
4	1			1	1	1	1	1		1		1			1		1	1				1	1
5	1			1	1	1	1	1		1	1	1	1	1			1	1	1				
6	1	1			1		1	1		1		1	1	1	1		1	1		1			1
7	1	1		1	1	1	1	1		1		1	1	1	1	1	1	1		1	1	1	

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8	1	1		1	1		1	1	1		1		1	1				1	1		1		1
9	1	1	1		1		1	1	1		1	1	1	1	1			1	1		1	1	1
10	1	1		1	1			1	1		1	1	1	1	1			1	1		1		1
11	1	1	1		1			1	1			1		1	1			1	1		1		1
12	1	1	1		1			1	1		1	1	1	1				1	1		1		
14	1	1		1	1			1	1	1	1		1		1	1	1	1	1		1	1	1
15	1	1		1	1			1	1	1	1	1	1	1	1	1	1	1	1		1	1	1
16	1	1		1	1			1	1	1	1	1	1	1	1	1	1	1	1		1	1	1
17	1	1		1	1			1	1	1	1	1	1	1	1	1	1	1	1		1	1	1
18	1	1		1	1			1	1	1	1	1	1	1	1	1	1	1	1		1	1	1
									2011														
1	1			1	1	1	1	1			1		1	1	1			1	1		1	1	1
2	1			1	1	1	1	1			1	1	1	1	1			1	1		1		
3	1			1	1	1	1	1			1	1	1	1	1			1	1	1	1	1	1
5	1			1	1	1	1	1			1	1	1	1	1			1	1	1		1	1
7	1	1		1	1	1	1	1			1		1	1	1	1	1	1	1		1	1	1
8	1	1		1	1	1	1	1			1		1	1				1	1		1		1
9	1	1	1		1	1	1	1			1	1	1	1				1	1		1		1
10	1	1		1	1		1	1			1	1	1	1				1	1		1		1
11	1	1	1		1		1	1			1		1					1	1		1		1
14	1	1		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1
15	1	1		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1
17	1	1		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1
18	1	1		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1

vation, cost of labor, amount of irrigation water applied per hectare, cost of transportation, fixed costs for agricultural production, and finally yield of major crops. In addition, climatic data from the nearest weather station for each of the 18 sites was gathered for calculating reference evapotranspiration of cotton crop at the given locations.

3. METHODOLOGY TO CALCULATE WATER PRODUCTIVITY

There are several definitions of water productivity (WP). The most commonly used definition [4] is given as the ratio of the crop yield, Y_{crop} (kg/ha), divided by the consumptive use of water by the crop, ET_a (m^3/ha), *i.e.*

$$WP = Y_{crop}/ET_a \qquad (1)$$

in which Y_{crop} = measured crop yield under natural and irrigated conditions, kg/ha; and ET_a = estimated/measured seasonal evapotranspiration or crop water use, m^3/ha. The above definition is independent of the source of water made available for ET_a, and assumes that any water losses that occur at field level, in the form of run-off and deep percolation, are recaptured and re-used somewhere else in the basin, ignoring or discounting some "co-benefits" such as improved water quality (particularly under Central Asian conditions where salinity is a major issue), increased crop production, increased reliability in water supply, decreased energy demands and carbon emissions, and reduced or delayed infrastructure investments [5] that accrue from improved application efficiency at field level. The source of water for ET_a may be a combination of one or more of the following: rainfall, groundwater, residual soil-moisture from previous season or irrigation water.

Sometimes, we are interested in the incremental change

in crop yields due to the addition of irrigation water to fields. Therefore, another productivity term called irrigation water productivity [6] is defined as follows:

$$WP_I = \left(Y_{crop} - Y_D \right) / V_I \qquad (2)$$

in which WP_I = irrigation water productivity of crop, kg/m³; Y_D = crop yield under dryland conditions (rainfall, residual initial soil-moisture content from previous season, groundwater contribution) without any irrigation, kg/ha; V_I = cumulative volume of irrigation water applied during the crop growing season, m³/ha. To calculate WP_I, information on crop production Y_D at different levels of natural water supply must be available.

The water productivity definitions provided above (**Eqs.1** and **2**) do not provide any indication of inefficiency of water application at field level. Sometimes, farmers apply 50% to 100% more water than the amount of water required by the crop; yet, the actual water use by crop (ET_a) only goes up slightly compared to its water use under normal conditions. In order to capture the inefficiency of water use by farmers, the following definition of water productivity is proposed here:

$$WP_G = Y_{crop} / V_{all} \qquad (3)$$

in which WP_G = gross water productivity, kg/m³; and V_{all} = volume of water applied to a field from all sources (rainfall, residual soil-moisture, groundwater, and irrigation water), m³/ha, and is calculated as follows:

$$V_{all} = V_{irri} + V_{GW} + V_{imc} + V_{rainfall} \qquad (4)$$

in which V_{irri} = volume of irrigation water applied to a field, m³/ha; V_{GW} = volume of groundwater contribution to crop root zone, m³/ha; V_{imc} = volume of initial soil-moisture content at the time of planting, m³/ha; and $V_{rainfall}$ = volume of rainfall received on the field during the crop growing season, m³/ha.

In order to calculate WP using **Eq.1**, the seasonal crop water use (ET_a) must be estimated for the given location. The most accurate methods of measuring ET_a are lysimeters, neutron probes, and gravimetric methods. However, since the 18 demonstration sites were scattered over a large area, and since no lysimeters and neutron probes were available, the ET_a was estimated using a standard soil-moisture balance equation [6,7]:

$$ET_a = R + I + F - Rf - \Delta S \qquad (5)$$

in which ET_a = seasonal crop evapotranspiration or water use, mm; R = rainfall during the growing season, mm; I = irrigation amount applied during the growing season, mm; F = net soil-moisture flux (taken positive into the rootzone) at the bottom of the crop rootzone, mm; Rf = runoff from the soil-surface, mm; and ΔS = change in soil-moisture content (taken as positive when the soil-moisture content increases over the season) within the crop rootzone during the crop growth season, mm. All the quantities on the right-hand-side of **Eq.5** must be carefully estimated in order to estimate seasonal crop water use. In using **Eq.5**, the most difficult variable to estimate is F, the net soil-moisture flux from/to the crop rootzone. In the absence of a high watertable, the net soil-moisture flux is always negative, and is basically due to deep percolation from irrigation and/or rainfall amount added to the crop rootzone. The change in the rootzone soil-moisture content is typically estimated using gravimetric sampling or neutron moisture meter. If a lysimeter is used, all the quantities on the right-hand-side of **Eq.6** are measured in order to compute the crop consumptive use on a daily, weekly, or seasonal basis. In the absence of lysimeters and soil-moisture sensing devices, a different method can be used to estimate the seasonal consumptive water use (ET_a) of a given crop. It is given as follows:

$$ET_a = \Sigma ET_a(i), \quad i = 1 \text{ to } N \qquad (6)$$

in which $ET_a(i)$ = estimated crop evapotranspiration on day i, mm/day; and N = number of days in the growth period for the given crop. $ET_a(i)$ is estimated as follows:

$$ET_a(i) = K_c(i) K_s(i) ET_r(i) \qquad (7)$$

in which $ET_r(i)$ = estimated evapotranspiration of a reference crop on day i, typically estimated using the available climatic data, mm/day; $K_c(i)$ = crop coefficient values as a function of different growth periods of the given crop; and $K_s(i)$ = soil-moisture stress coefficient on day i which is related to the maximum available soil-moisture content and the actual soil-moisture content in the rootzone on day i. In the literature, three different types of relationships are provided between K_s and the soil-moisture content in the rootzone. The following relationship is used in this paper:

$$K_s(i) = \ln\left(1 + PAW(i)\right) / \ln(101) \qquad (8)$$

in which PAW(i) = percent available water within the crop rootzone on day i, and is calculated using

$$PAW(i) = 100\left(\theta_a - \theta_{wp}\right) / \left(\theta_{fc} - \theta_{wp}\right) \qquad (9)$$

in which θ_{fc} = soil-moisture content at field capacity, mm; θ_{wp} = soil-moisture content at wilting point, mm; and θ_a = actual soil-moisture content, mm. Soil-moisture content on a volume-basis is calculated using the following equation:

$$\theta = \varphi \gamma_{bd} z_r(t) \qquad (10)$$

in which θ = soil-moisture content on a volume-basis; φ = soil-moisture content on a weight-basis; γ_{bd} = soil bulk density; and $z_r(t)$ = crop rooting depth, mm. Since it is tedious to measure soil-moisture content, θ_a, on a daily basis, frequently a soil-moisture balance equation is used

to estimate θ_a on a daily basis

$$\theta_a(i+1) = \theta_a(i) + I(i) + R(i) - ET_a(i) + GW(i) \quad (11)$$

in which i = index of day; I(i) = irrigation amount on day i, mm; R(i) = rainfall amount on day i, mm; and GW(i) = groundwater contribution on day i, mm. To use **Eq.11**, information on the soil-moisture content on the day of planting (i = 1), the dates and amounts of irrigation water applied (minus runoff from field), the dates and amounts of rainfall, and groundwater contribution to the crop rootzone on a daily basis must be known. Groundwater contribution, in mm/day, to the crop rootzone depends upon the soil texture, the evaporative demand of the atmosphere, and the depth of the watertable from the ground surface. **Figure 2** shows the dependence of groundwater contribution to crop rootzone as a function of soil-texture and depth of watertable from the ground surface [8]. Information from this graph was used to estimate groundwater contribution to crop rootzone on a daily basis.

In **Eq.7**, the ET_r was estimated using the Penman-Monteith equation [9] along with the local climatic data available from the weather stations operated by the Meteorological Departments of Uzbekistan and Tajikistan. The daily climatic data on sunshine hours, solar radiation, minimum and maximum temperatures and wind speed were available from the weather stations. The reference crop considered was short grass. Since there were no locally calibrated crop coefficients for cotton, the crop coefficients for cotton were obtained from FAO-56 report [9]. Since crop coefficients depend upon the climatic conditions and growth characteristics of given crop vari-

ety, use of general crop coefficients provided in FAO-56 might introduce some error in the estimation of ET_a, and this error was considered acceptable for the current large-scale study.

4. RESULTS AND DISCUSSION

Yield data for the 13 demonstration sites in Uzbekistan and the 5 demonstration sites in Tajikistan was obtained from the farmers. Crop yield data along with the cost of production, and net profits are presented in Table 3 for the years 2009, 2010 and 2011. During the 2010 and 2011 irrigation seasons, all the demonstration farmers did not grow cotton on their demonstration fields. Hence, the number of cotton fields was less than 18. Yields of cotton from the demonstration sites ranged from 2000 kg/ha to 5500 kg/ha (**Figure 3**). This difference in yields was due to a combination of factors such as quality of advisory services received, the quality and quantity of seed used, the availability and quality of inputs received or applied by farmers, crop variety, and the irrigated cotton production knowledge-base of the farmers. Two things are obvious from **Figure 3**. First, the average yield of cotton from the demonstration sites in Tajikistan was lower (less than 3000 kg/ha) than the average yield of cotton from demonstration sites in Uzbekistan (about 3500 kg/ha). This difference in yields may be partly explained by the availability of credit for purchasing agricultural inputs plus application of land use practices which are also supported and monitored by the State. In Uzbekistan, since cotton is one of the two crops that is mandated by the State, the State provides the nec-
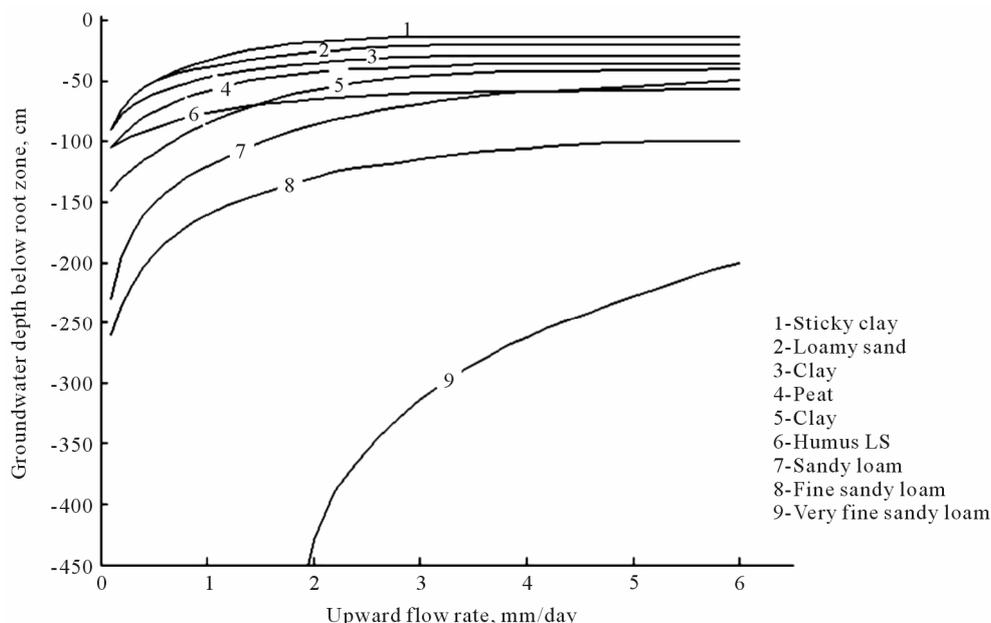
Figure 2. Groundwater contribution to crop rootzone.
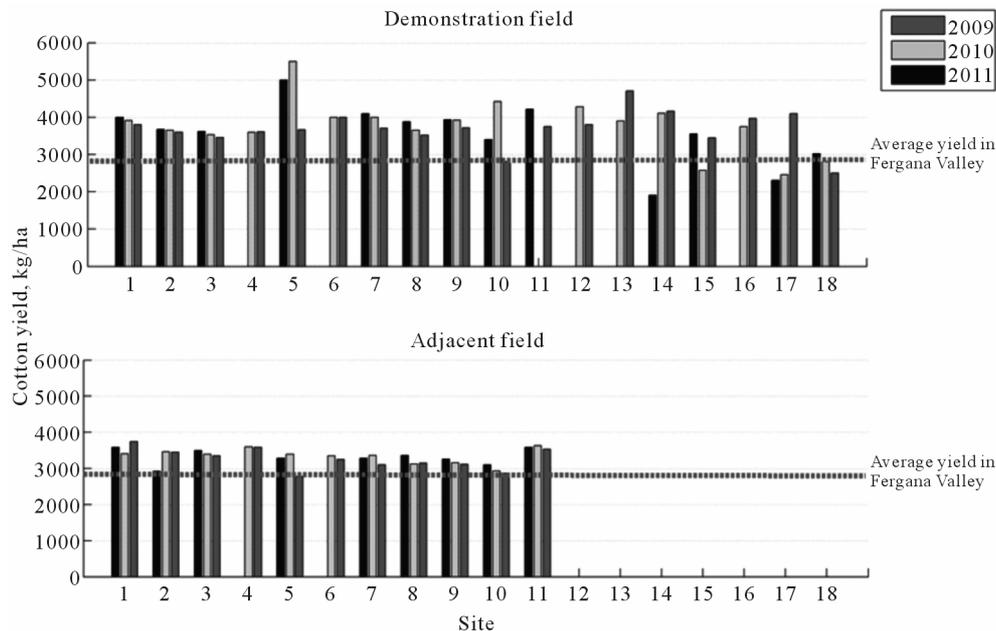
Figure 3. Cotton yields for the demonstration sites and the adjacent fields.

essary credit to farmers for purchasing all the necessary inputs to grow cotton, and the district-level government officials prod the farmers to apply irrigation water on-time according to the irrigation norms (though outdated), and to apply appropriate plant protection measures. Though data on the type and quantity of each input was collected, no information was collected on the quality and the timing of the inputs. In the case of Tajikistan, no such credit is available to farmers, and hence no such monitoring of inputs including water is done by the State. Secondly, as mentioned elsewhere, 2009 and 2010 (more rainfall and more water was available for irrigation during the vegetation period) were considered as wet years whereas 2011 was a dry year (less rainfall and less amount of irrigation water was available during the vegetation period). Yet, on the average, there was no significant difference in the yield of cotton between the wet and dry years. The farmers used irrigation water efficiently by under-irrigating the crop during the dry year. Under-irrigation was practiced not by choice, but by default!

Cotton yields from the adjacent fields are also shown in **Figure 3**. No data was available from the adjacent fields in Tajikistan. As expected, the average yields from the adjacent fields were lower (around 3300 kg/ha) than the average yields (3700 kg/ha) obtained from the demonstration sites in Uzbekistan. The demonstration field farmers implemented a variety of "innovations" or improved agronomic and irrigation practices, as shown in **Table 2**, whereas the adjacent farmers were using one or more of the innovative practices implemented by the demonstration farmers. The average cotton yields in

Fergana Valley were about 2900 kg/ha, indicating that the average crop yields from the demonstration fields were 28% higher than the average crop yields in the area. From the above it is evident that there is a substantial opportunity to increase crop yields, and thus water productivity, in Fergana Valley through a combination of agronomic and irrigation water management interventions (**Table 2**). Since there was so much variability in the quality of inputs used at various demonstration sites (including crop varieties), it was not possible to identify the most important factors for increase in crop yields. Also, the yields of adjacent fields increased by 14% (above the average for Fergana Valley) suggesting that, with time, more farmers would adapt these interventions to raise the average yield of cotton in Fergana Valley. Some of the demonstration field farmers were using some additional innovative agronomic practices such as irradiation of seed, plastic mulching, and passing irrigation water through a magnetic field. All of these practices contributed to decent increases in crop yields. However, detailed field investigations are still underway to confirm and document the benefits of using these technologies so that they can be disseminated through the Innovation Cycle.

To estimate water productivity of cotton, the consumptive use of cotton crop was estimated using a simulation model (using **Eqs.7-11** in an Excel Spreadsheet) on all the 18 sites. The total amount of water supplied from all the sources-initial soil-moisture content, groundwater contribution, irrigation, and rainfall was also calculated for all the 18 demonstration sites. Information on daily rainfall amounts (in millimeters) and daily weather

conditions was obtained from the nearest weather station for each of the 18 demonstration sites. Then, the Penman-Monteith equation, as described in [9] was used to compute the daily evapotranspiration of a reference crop (short grass), ET_{ref}, for each of the 18 sites. Based upon the depth of the watertable and the soil-texture, daily groundwater contributions to the crop rootzone were estimated using **Figure 2**. Information on dates and amounts of rainfall, daily groundwater contributions, daily ET_{ref}, and dates and amount of irrigation water infiltrated into the crop rootzone for each site was used to calculate soil-moisture balance (**Eq.11**) in the rootzone. In the simulation, the following assumptions were made:

1) The soil-moisture content in the crop rootzone was assumed to be close to field capacity at the beginning of the season.

2) The maximum rooting depth of cotton was assumed to be 1.6 m. The active rooting depth at the beginning of the season was assumed to be 0.15 m, and the rooting depth was assumed to increase to its maximum rooting depth linearly by the end of vegetative period.

3) In situations where there was a high watertable, the maximum rooting depth was set equal to the highest level of the watertable which typically occurred during the second half of the crop growth season.

4) If the calculated soil-moisture content on any given day was higher than the field capacity soil-moisture content for that soil, due to irrigation or rainfall, the soil-moisture content was set equal to the field capacity soil-moisture content for that soil.

These simulated values of daily soil-moisture content

were used to calculate the daily soil-moisture stress coefficient, K_s, using **Eq.8**, which was then used to estimate the daily actual evapotranspiration, ET_a, of cotton. The daily K_c values were obtained by linear interpolation of the values suggested by [9].

The seasonal amount of irrigation water applied, the rainfall amounts received, the groundwater contributions to crop rootzone, and the simulated total consumptive water use of cotton crop were calculated (**Figure 4**) for all the sites. It is clear from **Figure 4** that the seasonal consumptive water use of cotton crop, ET_a, varied from 4500 m^3/ha to 8000 m^3/ha, depending upon the total amount of water supplied (TWA) from all sources, the timing of irrigations and rainfall amounts, and the local climatic conditions. The TWA to fields varied from 5000 m^3/ha to 12,000 m^3/ha. In general, the lowest total water applied and the lowest estimated ET_a occurred in 2011 because it was a dry year! On the average, the TWA values were higher in Tajikistan than in Uzbekistan. This may be partly due to the tighter monitoring that is exercised on following the irrigation norms in Uzbekistan. Based upon the data in **Figure 4**, a quadratic relationship ($R^2 = 0.70$) was found between TWA and ET_a, with ET_a values flattening at higher values of TWA (**Figure 5**). This relationship between TWA and ET_a is not a new finding but confirms the existing knowledge [10]. The ET_a value reaches an upper limit under a given set of climatic conditions; hence, at higher values of TWA, a large decrease in TWA results in a small decrease in ET_a, and thus a small decrease in crop yields. This probably explains why there was no significant difference in the
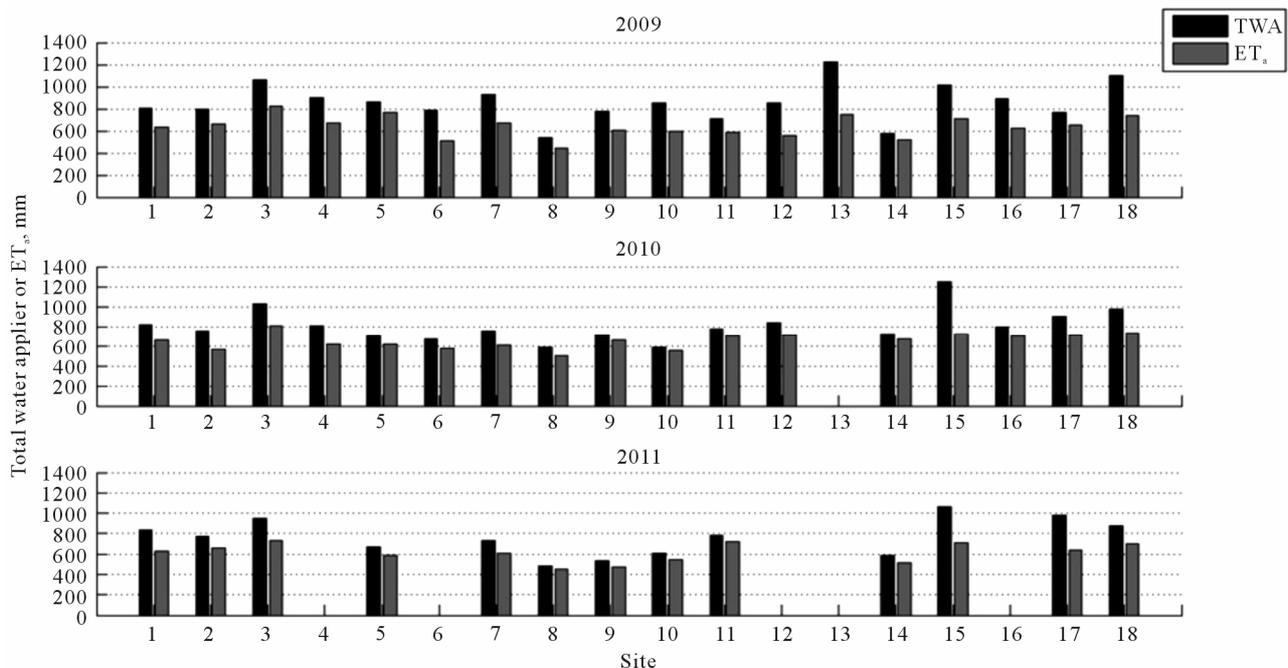
Figure 4. Total water applied and simulated ET_a values for the demonstration sites.
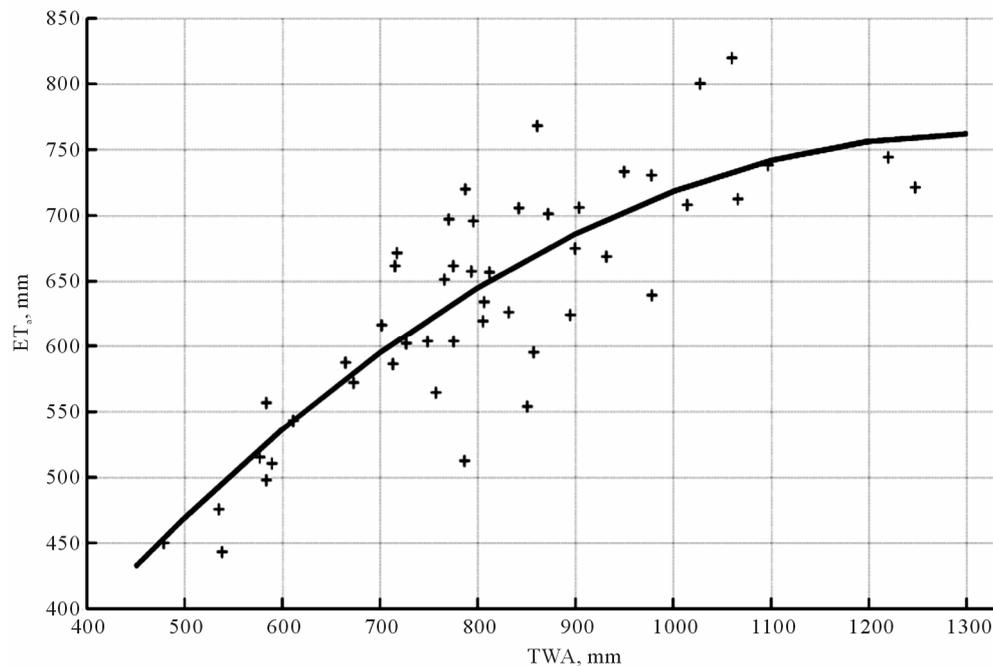
**Figure 5.** Relationship between total water applied and simulated ET_a values for the demonstration sites.

average yield of cotton (**Figure 3**) between 2011 (a dry year) and 2009 and 2010 (wet years).

A regression analysis was also performed between crop yield data (**Figure 3**) and the simulated ET_a data (**Figure 4**) from the demonstration fields. No definite correlation was found between the two variables. This is no surprise because, though water is the most important input for crop production, crop yields at any given location also depend upon a variety of other factors such as crop variety, seed quality and seeding rate per hectare, soil fertility and fertilizer management, plant protection measures used, climatic conditions and degree of unevenness of land surface, etc. The collected data was not sufficient to do a multiple regression analysis between the input variables and crop yields in order to identify the most important input variables for increasing crop yields. Some or all of these inputs, in addition to water, contributed to achieve higher crop yields.

Water productivity (WP) values (**Figure 6**) were calculated based upon crop yield (**Figure 3**) and ET_a values (**Figure 4**). The WP values ranged from 0.35 kg/m³ to 0.89 kg/m³, with an average value of 0.58 kg/m³. The average TWA value was 28% higher than the ET_a value, indicating that, on the average, the field irrigation systems were operating at 78% application efficiency. The remaining 22% was lost from the fields. However, from a basin perspective, if all of this 22% water was used by some other farmers somewhere else in the project area or returned to the same stream, then this water was not really lost, implying that no real water savings would

accrue by improved application efficiency at field level. However, since more than 60% of the area irrigated in Tajikistan and Uzbekistan receives pumped water, there would be considerable savings in energy used for pumping irrigation water if the application efficiency is further improved. In addition, there would be a proportionate decrease in the amount of salts returning to the stream. Improved application efficiency is achieved by decreasing surface runoff and/or deep percolation water (from fields) through improved layout of irrigation systems and proper irrigation scheduling [11]. However, improved application efficiency comes at a cost! Therefore, one has to weigh the costs and benefits (reduced energy costs, reduction in salinity of downstream areas and the resulting increases in crop yields, improved reliability of water supply to downstream areas) of improving application efficiency at field level. In this research no WP_I values were calculated because no information was available on Y_D values for the demonstration sites.

Sometimes the average values do not tell the whole story. Therefore, we need to look at the range of values for these variables. For example, the WP values ranged from 0.35 kg/m³ to 0.89 kg/m³ which suggest that there is a significant potential for the farmers that are at the lower-end to improve their water productivity through improved water management and/or agronomic practices, depending upon their situation. Similarly, the range of values for ET_a (4500 m³/ha to 8000 m³/ha) suggest that some fields are under-irrigated. Yet, the decrease in yield from the under-irrigated, *i.e.* deficit irrigated, fields was
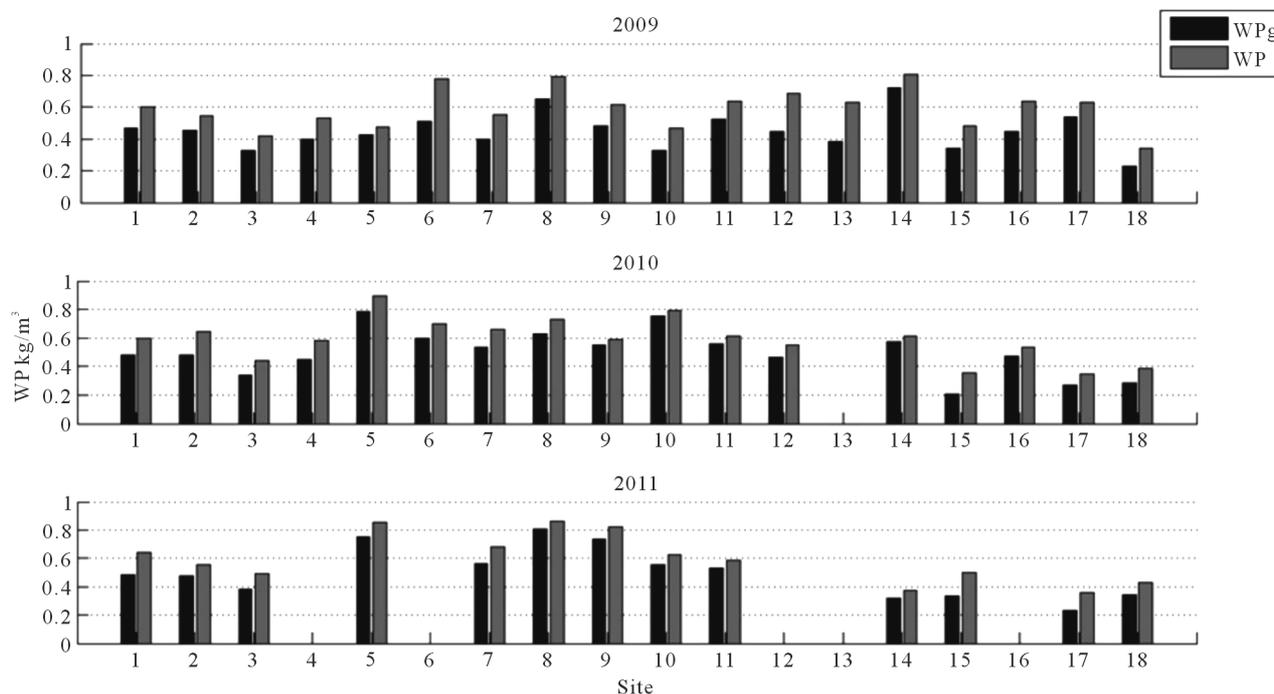
Figure 6. Water productivity and gross water productivity of cotton.

not significantly different from the fields that did not experience water stress, resulting in higher WP. Considering the range of values for TWA and ET_a indicates that the application efficiency can be significantly lower and higher than the average application efficiency of 78% in this case. Significantly higher than 78% application efficiency cannot be achieved without some level of under-irrigation, and consequently some reduction in crop yields. Conversely, significantly lower than 78% application efficiency would result in waterlogging (though it is equally likely that the inefficiency is due to high run-off than deep percolation) and reduced crop yields. This shows the potential for increasing WP by addressing the issue of inequity in water distribution which is a major problem in irrigation projects [12]. Thus there are two avenues for improving water productivity in irrigation projects-through improved technical and agronomic practices at field level, and by improving equity and reliability in water supply to farmers.

Finally, the net profit from crop production was calculated as the difference between gross returns from crop production and the cost of production (**Table 3**). The net profits ranged from $173 to $1911, depending upon the quality of cotton lint, irrigation and financial management skills of the farmer, and the market price for cotton. The net profits were higher in years 2010 and 2011 compared to year 2009 because the market price for cotton was higher during 2010 and 2011. The average net profit was higher in Tajikistan compared to Uzbekistan because the farmers in Tajikistan sold their cotton in

open market compared to the farmers in Uzbekistan where the cotton was sold to the government at the price fixed by the government. Comparing the data on net profits (**Table 3**) with the data on WP (**Figure 6**), it is clear that a high value of WP does not necessarily mean high net profit to the farmer. Because of the earlier mentioned co-benefits of "efficient" irrigation [5], the irrigation system managers would be more interested in improving water productivity through efficient irrigation (deficit or under-irrigation) practices, whereas the farmers are more interested in increasing the net profit per unit area. For farmers, in general, more water means more yields. These objectives are conflicting with each other. From their experience in Tunisia [13], a combination of water pricing and subsidies for improved technologies are required to reconcile this divergence of interests of farmers and irrigation system managers.

5. SUMMARY AND CONCLUSIONS

A total of 18 demonstration fields were selected in Fergana Valley (13 in Uzbekistan and 5 in Tajikistan) where the farmers were provided with a set of agronomic and irrigation management interventions to improve yields and water productivity of cotton. The average yields of cotton, for the years 2009, 2010 and 2011, from the demonstration fields and the adjacent fields were, respectively, 28% and 14% higher than the average yields for Fergana Valley. The total water applied (TWA) and the ET_a values were calculated for all the 18 demon-

Table 3. Cost of production, gross returns, and net returns from the demonstration sites for years 2009-2011.

Site №	Country	Province	2009					2010					2011			
			Area, ha	Total expenses	Yield	Gross revenue	Net profit	Area, ha	Total expenses	Yield	Gross revenue	Net profit	Area, ha	Total expenses	Yield	Gross revenue	Net profit
				$/ha	kg/ha	$/ha	$/ha		$/ha	kg/ha	$/ha	$/ha		$/ha	kg/ha	$/ha	$/ha
1	Uz	Andijan	6	834	3800	1393	560						6	1472	4000	2347	875
2	Uz	Andijan	14	821	3600	1212	392						6	1079	3600	1532	453
3	Uz	Andijan	6.5	1096	3460	1269	173						11.5	1178	3620	1572	395
4	Uz	Andijan	7	855	3610	1221	365	2	948.2	3600	1310	362					
5	Uz	Andijan	16.4	733	3660	1637	904	3	1017	5500	2879	1862	3	1379	5000	2559	1179
6	Uz	Fergana	4.8	857	4000	1360	503	4.5	577.1	4000	1593	1015					
7	Uz	Fergana	2	1288	3700	1607	320	2	731.7	4000	1246	514	1	1415	4100	1768	353
8	Uz	Fergana	4	648	3520	1412	763	4	982.9	3650	1934	951	0.15	1050	3887	1623	573
9	Uz	Fergana	2.5	838	3720	1116	278	4	622.8	3925	1557	934	3	756	3930	1631	876
10	Uz	Fergana	2.2	830	2800	1020	190	4.2	573	4420	1691	1118	2.5	1122	3380	1458	336
11	Uz	Namangan	10	684	3750	1294	610	6	1026.4	4280	1315	288	10	834	4210	2689	1855
12	Uz	Namangan	2	735	3800	1405	670	2	506.6	3900	1545	1038					
13	Uz	Namangan	2	857	4700	1589	732										
14	Taj	Soght	2.4	873	4160	1725	852	2.4	1004.4	4100	2596	1592	2.4	560	1900	1120	560
15	Taj	Soght	4.2	763	3440	3422	2659	4.2	884.1	2580	1976	1092	4.2	877	3548	2765	1888
16	Taj	Soght	1	1067	3970	1824	757	1	912	4150	2623	1711					
17	Taj	Soght	1.6	944	4100	1699	755	1.3	749.2	3200	2023	1273	1.3	651	2308	1360	710
18	Taj	Soght	2	966	2500	2877	1911	2	1112.9	2800	1949	836	2	1115	3020	2955	1839

stration sites for the irrigation seasons of 2009, 2010 and 2011, and these values for TWA and ET_a ranged, respectively, from 5000 m^3/ha to 12,000 m^3/ha and 4500 m^3/ha to 8000 m^3/ha, suggesting a quadratic relationship between TWA and ET_a, with ET_a values flattening off at higher values of TWA. During the three irrigation seasons, the calculated WP values ranged from 0.38 kg/m^3 to 0.89 kg/m^3, indicating that the farmers with a WP value less than the average WP of 0.58 kg/m^3 have a high potential to increase crop yields (and thus WP) through improved irrigation and agronomic practices (including selection of appropriate crop variety). Cotton yields in year 2011 (dry year) were not significantly different from the yields achieved during 2009 and 2010 (wet years), which is basically explained by the quadratic relationship between TWA and ET_a.

On the average, the TWA values were 28% higher than the ET_a, suggesting an average application efficiency of 78%. The remaining 22% of the water is lost from individual fields, but may or may not be lost from the basin. This needs to be carefully evaluated for each

project. Considering the fact that more than 60% of the water used for irrigation in Tajikistan and Uzbekistan is pumped from rivers and collector drains, even if all this 22% of the water returns to the stream without any degradation in water quality, considerable energy savings would accrue from improved water management at field level. Since salinity of return flows is also a major issue in Central Asia, improved efficiency at field level would alleviate the problems of salinity in lower reaches of the river basins. An average application efficiency of 78% suggests that there were some fields that were under-irrigated (yield losses due to water stress), and some fields that were over-irrigated (yield losses due to leaching of fertilizers and temporary waterlogging conditions). Addressing the issue of inequity and reliability in water supply, through improved water management, would also increase crop yields and water productivity from project areas. In general, there is significant potential for increasing water productivity in Central Asia through a combination of improved agronomic and irrigation practices at field level, and improved equity and reliability in

water delivery to fields.

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