A simple and farmer-friendly decision support system for enhancing water use efficiency in agriculture: tool development, testing and validation

Kaushal K. Garg*, Suhas P. Wani and Mukund D. Patil

ICRISAT Development Centre, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, India

In the semi-arid tropics (SAT) farmers practice calendar-based irrigation scheduling, which generally results in over irrigation and poor water use efficiency. The lack of a simple decision tool to decide timing and quantity of water to be applied is a bottleneck. An Excel-based decision support system termed Water Impact Calculator (WIC) is developed using data collected at the ICRISAT, which were validated at three pilot sites on farmers' fields in Rajasthan, Gujarat and Telangana. Field studies were conducted under two land-form treatments (broad bed and furrow (BBF) and flat fields); and irrigation water was applied following two different methods (drip and flood). The data collected at micro-watershed at the ICRISAT and three other sites showed that WIC could be used under wide range of soil and rainfall conditions. WIC simulated soil moisture was comparable with the observed moisture data, which forms the basis of irrigation scheduling. The WIC-based water balance at these experimental sites showed that number and amount of irrigation could be reduced by 30–40% using WIC-based irrigation scheduling without compromising the crop yield. The WIC could be a potential tool for water resources planning and efficient management at the field and watershed scale in the SAT.

Keywords: Consumptive water use, semi-arid tropics, water impact calculator, irrigation scheduling, water balance.

Introduction

WITH the increase in population pressure, economic growth and technological advances, natural resources are exploited for ensuring food, fodder and energy security, but at the cost of resource degradation[1]. It is anticipated that total food demand in 2050 will be double (approximately 11.2 billion tonnes) the current production level[2–6], whereas freshwater availability in most of the river basins (except Sub Saharan Africa) is already used for domestic, industrial and agricultural purposes. There is very little scope for augmenting freshwater resources which, therefore, demands improvement of resource use efficiency to meet the freshwater demand for increasing food production.

Agriculture is the largest consumer of the freshwater and utilizes nearly 70% of total amount in crop lands. Inappropriate management of water resources results in low crop yields, poor water use efficiency (WUE) and increased water demand for agriculture. Conservation and efficient use of water resources at both micro- and meso-scale (farmers' field and watershed scale) are essential for enhancing crop yield, productivity and income. To utilize the water resources more efficiently, there is an urgent need to enhance WUE through enabling farmers to adopt need-based irrigation scheduling and efficient irrigation methods in place of calendar- based scheduling of irrigation.

Due to inherent variability of bio-physical (soil hydraulic parameters and soil depth), topographical and land management (cropping sequence and time of sowing) factors, calendar-based irrigation scheduling does not always match with crop water requirement, resulting in reduced crop yields and poor WUE. Therefore, there is need to follow specific water application to optimize use of the available water resources. There are a number of decision making tools (e.g. CROPWAT)[7] capable of doing water balance and irrigation scheduling for different cropping systems. Use of these modelling tools is mainly limited to the scientific community due to complex parameterization. Currently available software/models either are data-depending or might require high-quality subject expertise. Moreover, these tools provide irrigation scheduling based on single time run, and there is no other means to modify the recommendations with follow-up rainfall events and actual farmers' practices in due course. The availability of a decision making tool that is simple to use and technically robust can help farmers for applying irrigation according to need rather than adopting the calendar-based irrigation application.

---

*For correspondence. (e-mail: k.garg@cgiar.org)

Moreover, using such tool, farmers and other practitioners (stakeholders) should be able to decide suitable cropping system and cultivation intensity for their fields at the watershed or community scale; and would also be potentially useful in large scale irrigation planning and management (for example, canal water release and water allocation).

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is one of the premier institutes working for enhancing food security, crop productivity, income and livelihood of small and marginal farmholders in semi-arid tropics; and it has vast research and development experience in natural resource management. A number of micro-watersheds (3–10 ha) located at the ICRISAT research station in Patancheru have been intensively monitored for hydrology (surface runoff and soil moisture), weather (daily rainfall, maximum and minimum temperatures, solar radiation, wind speed and relative humidity), crop yields along with biophysical characterization of the environment. A decision support system called 'Water Impact Calculator' (WIC) is developed using strategic data collected at the ICRISAT research station along with supporting literature through a desktop study. Specific objectives of the current study are: (i) developing a simple and user-friendly WIC for analysing field water balance and translating the results into irrigation scheduling; (ii) testing and validation of WIC decision support system in different range of soils, climate and cropping systems both at research station and farmers' fields.

Methodology

Theoretical considerations

Water balance is essential as a primary step to quantify resource availability and various demands at a given landscape. One dimensional water balance model is assumed to capture field scale hydrology in current analysis. Rainfall as a source of water is partitioned into different hydrological components as defined by mass balance equation such as

$$\begin{aligned}\text{Rainfall} = {} & \text{surface runoff} + \text{groundwater recharge}\\ & + \text{evapotranspiration (evaporation + transpiration)}\\ & + \text{change in reservoir/pond storages}\\ & + \text{change in soil moisture storage.} \qquad (1)\end{aligned}$$

In the above equation, a fraction of rainfall which is stored into vadoze zone is known as green water; and rainfall stored/partitioned into groundwater aquifer, water harvesting structures and surface runoff is known as blue water[8]. Description of hydrological processes, system parameters and modelling methodology adopted in the current study are described below.

Runoff estimation: Surface runoff is the water flow that occurs when top soil is saturated during or after the rain event and excess rainwater flows over the landscape. Runoff is an important hydrological process which is controlled by soil biophysical, climatic, topographical and land management factors (soil type, land slope, land use and land management practices). The empirical runoff equation of the soil conservations service (SCS)[9] was used to estimate surface runoff in WIC such as

$$Q = \frac{(P - I)^2}{P - I + S}, \qquad (2)$$

where Q is surface runoff, P the precipitation, I the initial abstractions and S is the retention parameter which depends on soil physical properties, topography and land use-land management factors.

Retention parameter and initial abstraction are defined as

$$S = 25.4\left(\frac{1000}{\mathrm{CN}} - 10\right), \qquad (3)$$

$$I = 0.2S. \qquad (4)$$

where CN is the curve number of a day under average soil moisture condition (CN_2). WIC calculates daily curves number value based on antecedent moisture content of top soil layer (assumed for 15 cm depth in the current analysis). Curve number for three types of moisture situation is defined in WIC: dry, medium and wet soil. Dry represents soil moisture status reaching closer to permanent wilting stage and wet when the soil moisture level is at field capacity. The curve number for dry (CN_1) and wet (CN_3) situation is defined as[10]

$$\mathrm{CN}_1 = \mathrm{CN}_2 - \frac{20(100 - \mathrm{CN}_2)}{(100 - \mathrm{CN}_2 + \exp[2.533 - 0.0636(100 - \mathrm{CN}_2)])}, \qquad (5)$$

$$\mathrm{CN}_3 = \mathrm{CN}_2 \cdot \exp[0.00673 \cdot (100 - \mathrm{CN}_2)]. \qquad (6)$$

WIC initially assigns CN based on average land slope as defined by Hawkins[11]. After initiating CN per day, CN for subsequent days is estimated based on the available moisture in top 0–15 cm layer (eqs (5) and (6)).

Soil water balance

Soil water balance is the most crucial factor as it is the basis for irrigation scheduling. It is assumed that moisture in soil profile varies between field capacity and permanent wilting point. After separating runoff from rainfall,

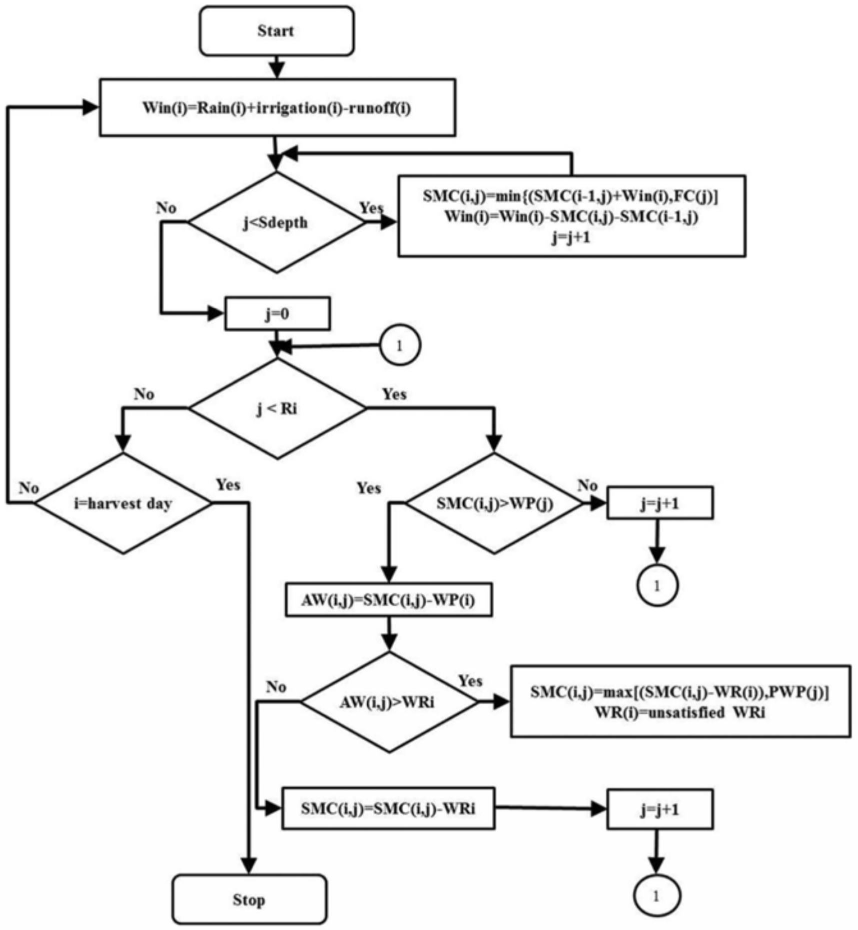

Figure 1. Flow diagram of layer-wise soil moisture estimation in WIC (Win, water input; *i*, time (day); *j*, depth; S depth, total soil depth; SMC, soil moisture content; FC, field capacity; R, root depth; WP, wilting point; PWP, permanent wilting point, AW, available water, WR, water required).

effective rainfall is allowed to infiltrate into soil. After filling soil pores up to the field capacity, surplus water is allowed to move down in subsequent layers (Figure 1). Moisture in each centimeter soil layer is defined by mass balance approach such as

$$\text{Soil moisture at day}_i = \text{rainfall} + \text{irrigation applied} + \text{soil moisture at day}_{i-1} - \text{runoff} - \text{evaporation} - \text{transpiration} - \text{deep percolation} \quad (7)$$

Deep percolation

The amount of excess infiltrated water after satisfying soil storage capacity is allowed to drain out from bottom (boundary) of the profile. This water either joins groundwater aquifer or partially contributes to the base flow at downstream location (not partitioned into base flow in the current version).

Evapotranspiration estimation

Evapotranspiration (ET) comprises two basic hydrological components: (soil) evaporation and (plant) transpiration. Evaporation is the vapour movement from earth surface, soil (green water) and water bodies (blue water) to atmosphere; whereas vapour movement through plant stomata is known as transpiration. Evaporation and transpiration, however, are two processes/components of hydrological cycle but their separation and quantification are challenging owing to its complexity and interdependability.

Reference crop evapotranspiration

Reference crop evapotranspiration (ET_0) is ET under a situation when a large area is covered uniformly with growing vegetation (usually considered as alfalfa) and the water availability for the plants is non-limiting[12,13]. WIC calculates ET_0 from meteorological parameters (maximum and minimum temperature, relative humidity, wind speed and solar radiation) using Penman–Monteith method[14]; or alternatively it also could be directly taken from other sources and used as input into the model. ET_0 is the parameter describing daily evaporative demand of a given location and is the primary basis for calculating

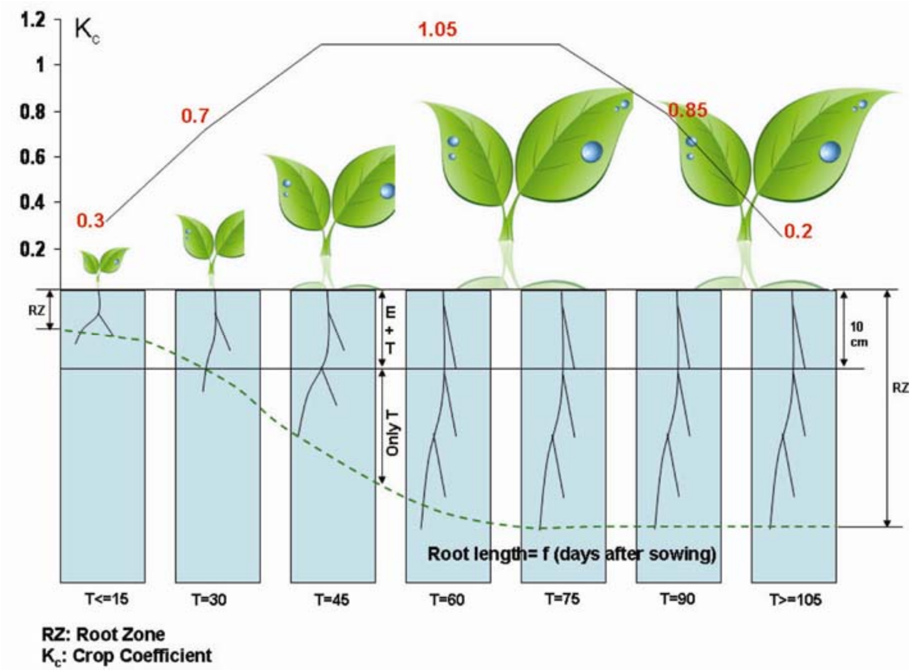

Figure 2. Conceptual representation of root and top growth of crops. Crop coefficients of winter wheat at every 15 days interval are shown to represent variable crop water demand. Total soil profile is divided into two compartments: soil moisture in surface 10 cm sinks under evaporation and transpiration process; available soil moisture in rest of the root zone is utilized by transpiration process. Root length/growth/zone is captured by empirical function (*s*-curve) in which input is crop stage (date after sowing).

actual evaporation and transpiration on a given boundary conditions.

Actual evapotranspiration

After obtaining or estimating ET$_0$, WIC calculates actual evaporation and transpiration based on imposed surface boundary conditions and moisture availability in top soil layer and root zone. A conceptual diagram of crop and root growth is shown in Figure 2 (K_c values are shown for winter wheat). We considered that available soil moisture in the top 10 cm layer will contribute to satisfying evaporation demand; whereas moisture up to root zone will be available for crop use (for transpiration). Moreover, it is assumed that evaporation from the landscape is inversely proportional to vegetative growth. After achieving full vegetative crop growth ($K_c \geq 1.0$), evaporation will be negligible.

Mathematically, crop water requirement (CWR) and evaporation demand (ED) are described as

$$\mathrm{CWR} = K_c \times ET_0, \tag{8}$$

$$ED = (1 - K_c) \times ET_0, \tag{9}$$

$$\text{if : } \sum_{j=1}^{\text{rootzone}} \mathrm{AWC} > \mathrm{CWR} \ \text{ then } \ T = \mathrm{CWR}$$

$$\text{otherwise } T = \sum_{j=1}^{\text{rootzone}} \mathrm{AWC}, \tag{10}$$

$$\text{if : } \sum_{j=1}^{10\text{ cm}} \mathrm{AWC} > ED \ \text{ then } \ E = ED$$

$$\text{otherwise } E = \sum_{j=1}^{10\text{ cm}} \mathrm{AWC}, \tag{11}$$

where AWC is the available water content (field capacity – permanent wilting point). WIC computes water balance for each cm of soil layer up to defined soil depth (one dimensional) as shown by *j* in eqs (10) and (11).

Reservoir hydrology

WIC was not only targeted to analyse water balance at catchment-scale, but also to estimate water resources availability at meso-scale watershed (5–500 ha). Check dams and water harvesting storage structures play an important role in augmenting water resources at community or village scale. Garg and co-workers[15,16] showed that constructing small and medium water harvesting structures in watershed could harvest 30–60% of runoff water and enhance groundwater recharge in a semi-arid tropical regions. Water harvesting storage capacity developed in a given watershed or landscape could be provided on per hectare basis in WIC. Generated surface runoff is diverted through water harvesting structures and allowed to store it according to defined capacity and excess water is spilled-out from the watershed/field boundary. Reservoir hydrology of small or medium storage structures is described by the following mass balance equation

Water volume at day$_i$ = water volume at day$_{i-1}$
+ inflow received (runoff) + rainfall over the water body – evaporation from the water body – spillover amount – infiltration from reservoir bottom (artificial groundwater recharge) – water withdrawn or utilized. (12)

Development of WIC

Input data and model development

While developing WIC, it is primarily considered that tool should be simple and user-friendly in terms of data requirement. User should quickly enter input data relating to their farm; quickly understand the main water-related impacts and get irrigation scheduling. Microsoft excel is found a suitable computational platform for developing WIC. Different hydrological components (modules) were developed in excel sheets separately and integrated together using logical functions as shown by the flow diagram in Figure 3. Moreover, soil and weather parameters such as field capacity, permanent wilting point, ET_0 and crop growth parameters (crop coefficient and root growth) are used from the default values stored in the back-up files based on farmers' input about soil type, crop grown and site location. Figure 4*a* shows Excel interface which facilitates user to enter required soil, topographic, crop and land management inputs. Table 1 shows the list of input parameters needed to be entered by user.

Irrigation scheduling

The moment water availability in root zone reaches below the defined threshold, WIC calculates (i) total crop water requirement for following one week period by considering ET_0 and crop growth stage and (ii) analyse moisture holding capacity of elongated root zone at the given stage and choose minimum between (i) and (ii). Irrigation efficiency is an important parameter which describes that how much extra irrigation be applied to cover-up field completely, has also been considered during the calculation. Moreover, user is allowed to enter actual irrigation practices and amount of rainfall received during subsequent crop growth stages. On the basis of such information, WIC re-analyses water balance and modifies follow up recommendations. Figure 4*b* shows the summarized output sheet (date and amount of irrigation application and water balance components) generated by WIC.

WIC testing and validation

Strategic research data of micro watershed BW7

For testing WIC, we used research data collected at micro-watershed (BW7) in ICRISAT between 1996 and 2004. Depth-wise soil moisture on every 15 days interval and surface runoff was monitored under two different cropping systems, i.e. (i) soybean–chickpea sequential crops and (ii) soybean–pigeon pea intercrop. Site location and schematic diagram of BW7 field layout is shown in Figure 5. The general slope of the BW7 watershed is less than 2% and the soil is classified as Vertic Inceptisol. The soil profile in watershed varies from 30 to 90 cm and underlaid by a relatively coarse weathered material which also hold soil moisture and can be penetrated by plant roots for water uptake[17]. There is natural variability in soil depth within micro-watershed and classified into shallow (<50 cm soil depth) and medium deep (>50 cm soil depth) category. Effective soil depth in terms of depth of water extraction by plant roots is 110 cm and 125 cm in shallow and medium-deep soil respectively[17]. Total micro-watershed is divided into four blocks (Figure 5) where each block is further divided by two land management practices (flat system and broad bed and furrow system).

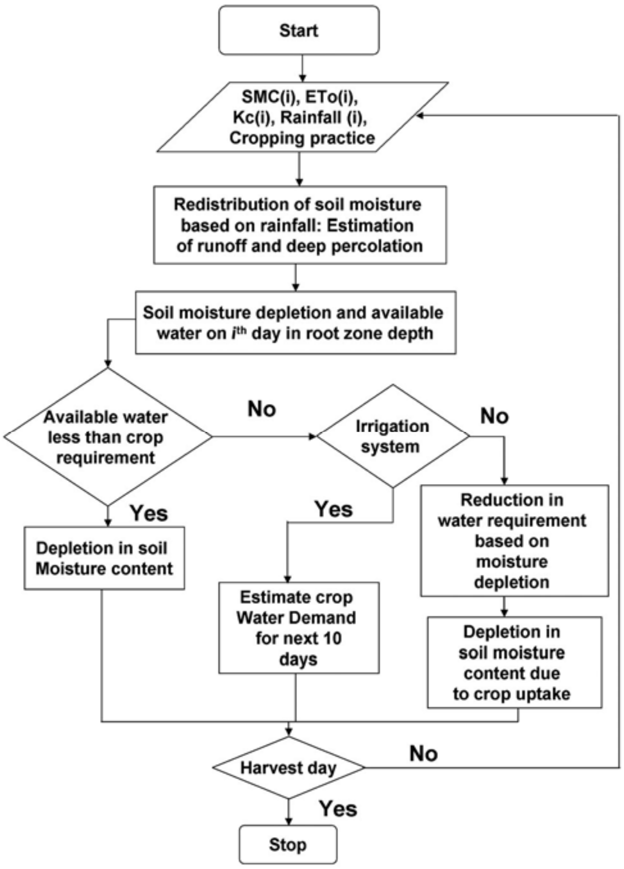

Figure 3. A flow diagram of the modelling methodology adopted using WIC.

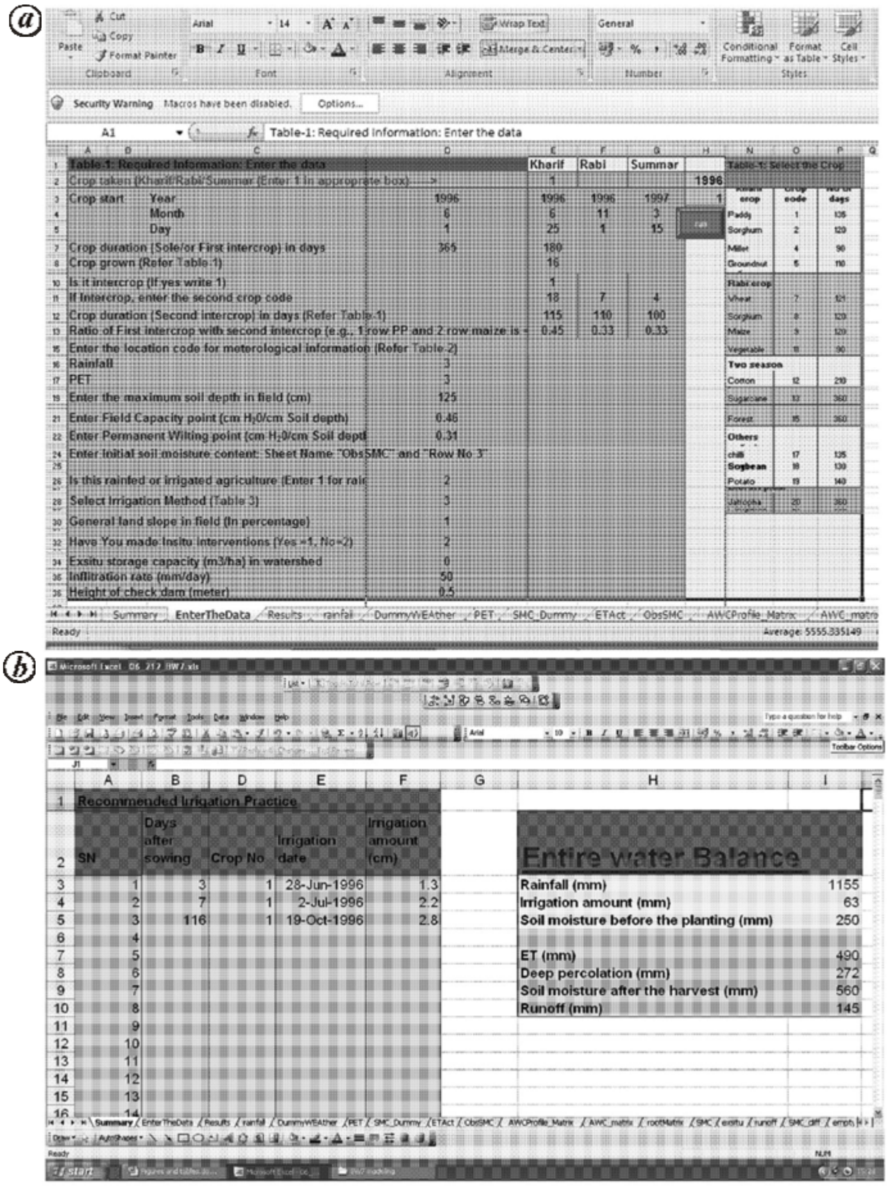

Table-1: Required Information: Enter the data

Table-1: Required Information: Enter the data		Kharif	Rabi	Summar	
Crop taken (Kharif/Rabi/Summar (Enter 1 in approprate box)---->		1			1996
Crop start Year	1996	1996	1996	1997	1
Month	6	6	11	3	
Day	1	25	1	15	
Crop duration (Sole/or First intercrop) in days	365	180			
Crop grown (Refer Table-1)		16			
Is it intercrop (If yes write 1)		1			
If Intercrop, enter the second crop code		18	7	4	
Crop duration (Second intercrop) in days (Refer Table-1)		115	110	100	
Ratio of First intercrop with second intercrop (e.g., 1 row PP and 2 row maize is =		0.45	0.33	0.33	
Enter the location code for meterological information (Refer Table-2)					
Rainfall	3				
PET	3				
Enter the maximum soil depth in field (cm)	125				
Enter Field Capacity point (cm H_20/cm Soil depth)	0.46				
Enter Permanent Wilting point (cm H_20/cm Soil dept	0.31				
Enter initial soil moisture content: Sheet Name "ObsSMC" and "Row No 3"					
Is this rainfed or irrigated agriculture (Enter 1 for rai	2				
Select Irrigation Method (Table 3)	3				
General land slope in field (In percentage)	1				
Have You made Insitu interventions (Yes =1, No=2)	2				
Exsitu storage capacity (m3/ha) in watershed	0				
Infiltration rate (mm/day)	50				
Height of check dam (meter)	0.5				

Table-1: Select the Crop

crop	code	days
Paddy	1	135
Sorghum	2	120
Millet	4	90
Groundnut	5	110
Rabi crop		
Wheat	7	121
Sorghum	8	120
Maize	9	120
Vegetable	11	90
Two season		
Cotton	12	210
Sugarcane	13	360
Forest	15	360
Others		
chilli	17	135
Soybean	18	130
Potato	19	140
Jatropha	20	360

Summary | EnterTheData | Results | rainfall | DummyWEAther | PET | SMC_Dummy | ETAct | ObsSMC | AWCProfile_Matrix | AWC_matrix

Recommended Irrigation Practice

SN	Days after sowing	Crop No	Irrigation date	Irrigation amount (cm)
1	3	1	28-Jun-1996	1.3
2	7	1	2-Jul-1996	2.2
3	116	1	19-Oct-1996	2.8
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				

Entire water Balance

Rainfall (mm)	1155
Irrigation amount (mm)	63
Soil moisture before the planting (mm)	250
ET (mm)	490
Deep percolation (mm)	272
Soil moisture after the harvest (mm)	560
Runoff (mm)	145

Figure 4. ***a***, WIC excel interface facilitates user to enter basic data to analyse water balance and also for irrigation scheduling. ***b***, A summary sheet of WIC output showing irrigation scheduling and seasonal water balance.

In soybean–chickpea sequential cropping system, soybean was sown in the third week of June and harvested during mid-October. The second crop of chickpea was grown soon after harvesting of soybean in the last week of October. Pigeon pea as an intercrop with soybean was planted in the third week of June and was harvested during middle of January. These crops were grown under rainfed conditions. WIC was run for all combinations of land management and cropping system (soil depth × land form condition × cropping pattern).

Model parameterization

Soil moisture retention properties (field capacity and permanent wilting point) were measured on point-based measurement, but they were further parameterized to capture field scale hydrology using the inverse optimization technique through excel-built solver program. Soil moisture measured at weekly time interval was used as auxiliary variable during the optimization process. Model performance was tested by visual fit and with number of statistical parameters. Model performance was validated by comparing the simulated surface runoff with the observed runoff. In absence of measured ET, simulated ET was correlated with observed crop yield using data obtained from different years.

Field experiments in farmers' fields

For testing the WIC, ICRISAT-led consortium with local partners (NGOs), irrigation company (Jain Irrigation

Table 1. Input data required for operating WIC

Parameters	Minimum/essential data	Optimum (but not essential)
Field scale analysis		
Soil information	Maximum soil depth	Field capacity
	Soil type	Permanent wilting point
	–	Initial moisture of soil profile
		Infiltration rate
Sowing details	Date of sowing	–
	Crop cultivating (code)	–
	Crop duration	–
Land topography	Land slope (%)	
Rainfed or irrigated land	Yes/no	
Rainfall	Update daily information	
Actual irrigation applied by user*	If irrigated, amount of irrigation applied by user on different dates	
Method of irrigation	Drip/sprinkler/flood	
Meteorological data/site location		For calculating ET_0
Watershed scale analysis		
Type of water interventions made in watershed	*In situ*/*ex situ*/no mgt (enter code)	
In case of *ex situ* interventions	Water harvesting potential created ($m^3\ ha^{-1}$)	
	Infiltration rate of reservoir bottom	

*Follow up recommendation could be refined or modified by providing actual information of water use.

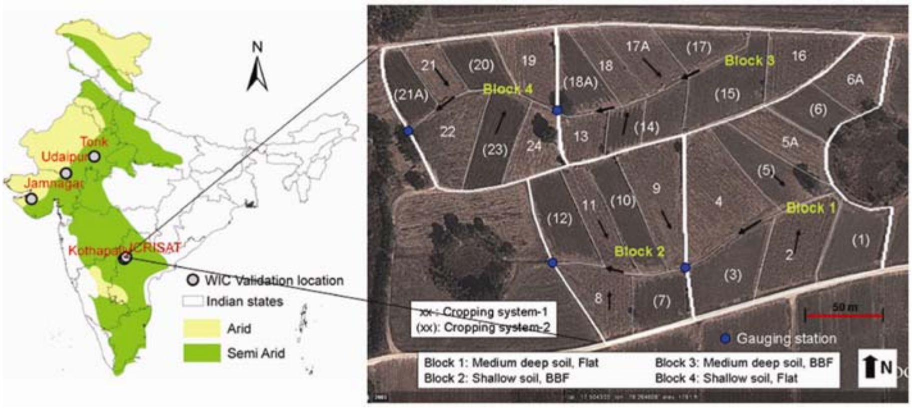

Figure 5. WIC testing and validation sites in Rajasthan, Gujarat and Andhra Pradesh; zoomed-in map shows Google Earth image of experimental layout of micro-watershed, BW7 at ICRISAT campus. BW7 watershed is broadly divided into four blocks based on soil depth and land form treatment, and each block is further divided into a number of plots (plot numbers from 1 to 24 are shown in the figure). Automatic runoff and sediment monitoring unit is installed at outlet of the each block.

Ltd) started farmers' participatory field trials during 2010–2012 in (i) Mota Vadala in Jamnagar, Gujarat; (ii) Kothapally in Ranga Reddy, Telangana; and from 2010 to 2013 in Dharola Tonk, Rajasthan (Figure 5). Experimental setup comprised two land form treatments: (i) broad bed and furrow practices (BBF) and (ii) flat land; and two irrigation methods: (drip and flood/furrow irrigation) were laid out using (split plot design) in four plots each of 1000 square meter area. Rain gauge stations were installed at all the experimental villages and rainfall was monitored daily. Soil physical properties (texture, field capacity, permanent wilting point, bulk density); and chemical properties (organic carbon, pH, EC, available S, B, Zn, P and K) were analysed for top soil layers of 0–15 and 15–30 cm (Table 2). Wheat crop was grown in the post-monsoon period (November–February) and groundnut was cultivated in monsoon (June–October) season. Dates of crop planting, fertilizer application, intercultural operation and harvesting were recorded. Fertilizer application and other field management practices were implemented according to general recommendations at respective experimental locations. Irrigations were scheduled using WIC calculations and exact quantity of water was applied as per recommendations. Gravimetric soil moisture content was measured from 0 to 15, 15 to 30, 30 to 45 and 45 to 60 cm soil depths at weekly interval. Crop grain yield and above ground biomass yield were estimated at the end of the crop harvest.

Table 2. Physical and chemical characteristics of soils at the experimental sites

State	Gujarat	Rajasthan	Telangana	Telangana
District	Jamnagar	Tonk	Ranga Reddy	Medak
Village/watershed/site	Mota Vadala	Dharola	Kothapally	ICRISAT
Soil physical parameters				
Soil type	Sandy–loam	Sandy–loam	Sandy–loam	Clay
Sand (%)	44 ($\sigma = 11$)	58 ($\sigma = 10$)	47 ($\sigma = 4$)	22 ($\sigma = 4.5$)
Silt (%)	20 ($\sigma = 2.5$)	27 ($\sigma = 7$)	22 ($\sigma = 2$)	19 ($\sigma = 3$)
Clay (%)	36 ($\sigma = 10$)	16 ($\sigma = 5$)	31 ($\sigma = 4$)	59 ($\sigma = 5$)
Bulk density (g/cm^3)	1.35 ($\sigma = 0.04$)	1.46 ($\sigma = 0.09$)	1.3 ($\sigma = 0.09$)	1.40 ($\sigma = 0.05$)
Field capacity (g/g)	0.18 ($\sigma = 0.04$)	0.20 ($\sigma = 0.07$)	0.28 ($\sigma = 0.02$)	0.32 ($\sigma = 0.07$)
Permanent wilting point (g/g)	0.10 ($\sigma = 0.06$)	0.12 ($\sigma = 0.04$)	0.19 ($\sigma = 0.06$)	0.23 ($\sigma = 0.05$)
Soil depth (cm)	30–60	80–120	30–90	50–120
Soil chemical parameters				
pH (–)	–	8.3 ($\sigma = 0.2$)	–	7.4 ($\sigma = 0.2$)
EC (ds/m)	–	0.42 ($\sigma = 0.27$)	–	0.2 ($\sigma = 0.1$)
Organic C (%)	–	0.59 ($\sigma = 0.09$)	1.04 ($\sigma = 0.1$)	0.80 ($\sigma = 0.3$)
Available S (mg/kg)	–	11 ($\sigma = 7$)	–	6.2 ($\sigma = 1.6$)
Available B (mg/kg)	–	2.1 ($\sigma = 0.4$)	–	0.3 ($\sigma = 0.1$)
Available Zn (mg/kg)	–	0.7 ($\sigma = 0.4$)	–	0.86 ($\sigma = 0.8$)
Available P (mg/kg)	–	10 ($\sigma = 13$)	–	15 ($\sigma = 0.4$)
Available K (mg/kg)	–	102 ($\sigma = 26$)	–	210 ($\sigma = 9$)
Meteorological parameters				
Average annual ET$_0$ (mm)	1520	1565	1730	1725
Average annual rainfall (mm)	605	685	750	850

*Number of samples analysed for each location is 32.

Results

WIC testing and validation

Performance of WIC in BW7 watershed: (i) *Water balance components.* WIC simulated soil moisture as compared with the measured data for different combinations of soil depth, land form condition and cropping system in BW7 watershed. Time series data of soil moisture fluctuations are shown between 1999 and 2003 in Figure 6. In this figure, smooth line (–) shows simulated numbers and circles (o) representing measured values. Simulated soil moisture using WIC is found comparable to observed soil moisture and followed similar trend. Moreover, the measured and simulated data are drawn on one to one line for all the eight treatments plots (Figure 7) during 1996 to 2004. In general, the simulated soil moisture is found in good agreement with the observed data. Root mean square error (RMSE) and coefficient of determination (R^2) statistics are found to be 1.8 cm and 0.88 respectively. Furthermore, the results (Figure 8) compare individually the average annual runoff generated from BBF and flat fields under shallow and medium deep soils. Simulated surface runoff from flat fields is found comparable with measured data, but is slightly overestimated (by 10–15%) for BBF plots.

(ii) *Crop yield and ET.* Average rainfall during crop growing season (June and February) was recorded as 825 mm (550–1300 mm) between 1996 and 2004 at ICRISAT campus. Table 3 shows average grain yield (maximum to minimum range), ET and crops which experienced water stress under different treatments (BW7 watershed). Crop yields measured from BBF system were found higher compared to flat fields but this difference was found insignificant ($P = 0.1$, Students *t*-test). There was a large variability found in crop yields from year to year and plot to plot as soybean and chickpea yields ranged from 0.65 to 2.36 t ha^{-1} and 0.06 to 1.38 t ha^{-1} in soybean–chickpea cropping system respectively (Table 3).

Chickpea yields were relatively higher in the medium deep soils compared to shallow soils due to extra moisture availability. Harvesting additional 50–100 mm moisture in sub-surface layers doubled the yield of chickpea crop. For example, 100 mm of ET produced chickpea yield 700 kg ha^{-1} in shallow soils whereas 1200 kg ha^{-1} chickpea production was recorded by 180 mm consumptive water use during year 1999.

In soybean/pigeon pea intercropping system, average crop yields in the medium deep soils in BBF plots were found better than in flat land form yields; but this difference was not significant among various treatments ($P \leq 0.15$). Soybean and pigeon pea yields ranged from 0.60 to 1.99 t ha^{-1} and 0.60 to 1.43 t ha^{-1} during different years respectively (Table 3). ET estimated from soybean/pigeon pea system (average 475 mm) was found relatively less compared to soybean–chickpea system (average 490 mm). Soybean/pigeon pea system experienced relatively less number of days under water stress compared to soybean–chickpea system (Table 3). Pigeon pea crop sown as intercrop with soybean had developed

Table 3. Crop yields, water use and water productivity of BW7 research station experiment between 1996 and 2004

Cropping pattern	Soybean–chickpea sequential cropping				Soybean/Pigeon pea intercropping			
Land form	Flat Fields		BBF Fields		Flat Fields		BBF Fields	
Soil depth (cm)	Shallow (<50)	Med deep (>50)	Shallow (<50)	Med deep (>50)	Shallow (<50)	Med deep (>50)	Shallow (<50)	Med deep (>50)
Soybean yield (t ha^{-1})	1.34 (0.69–2.26)	1.41 (0.67–2.36)	1.33 (0.65–2.30)	1.51 (0.68–2.36)	1.04 (0.6–1.73)	1.15 (0.53–1.82)	1.06 (0.59–1.57)	1.13 (0.53–1.99)
Chickpea yield (t ha^{-1})	0.59 (0.06–1.02)	0.92 (0.18–1.38)	0.67 (0.07–1.02)	1.11 (0.15–1.5)	–	–	–	–
Pigeon pea yield (t ha^{-1})	–	–	–	–	0.85 (0.6–1.13)	0.94 (0.6–1.25)	0.96 (0.7–1.43)	0.92 (0.5–1.38)
Total crop yield (t ha^{-1})	1.93 (1.1–3.3)	2.33 (1.6–3.7)	1.99 (1.2–3.3)	2.62 (1.8–3.6)	1.89 (1.3–2.7)	2.08 (1.3–2.9)	2.01 (1.5–2.5)	2.06 (1.2–2.9)
ET (mm)	476 (414–537)	507 (447–568)	473 (402–537)	509 (429–568)	467 (401–525)	484 (450–518)	465 (402–524)	487 (431–518)
Water stress period (%)	24 (15–36)	17 (8–30)	25 (15–38)	16 (8–30)	14 (04–26)	08 (01–18)	14 (04–27)	07 (01–19)

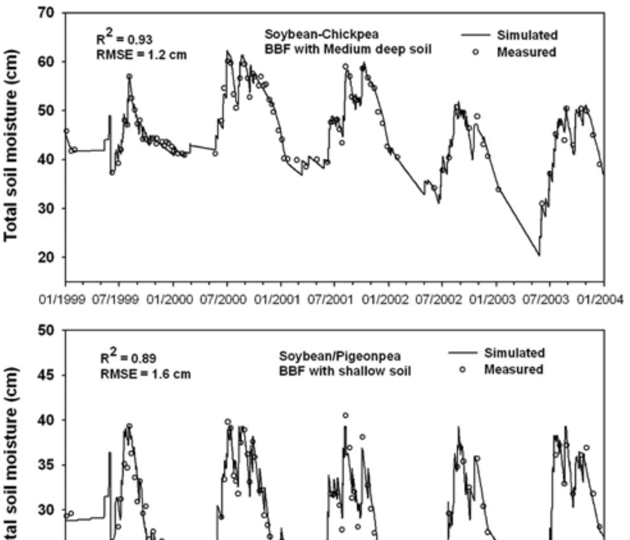

Figure 6. Time series data of total soil moisture content in selected field of BW7 watershed for five-year period. Comparison is made between simulated (shown by line) and measured (shown by circle) data under soybean–chickpea and soybean/PP cropping system.

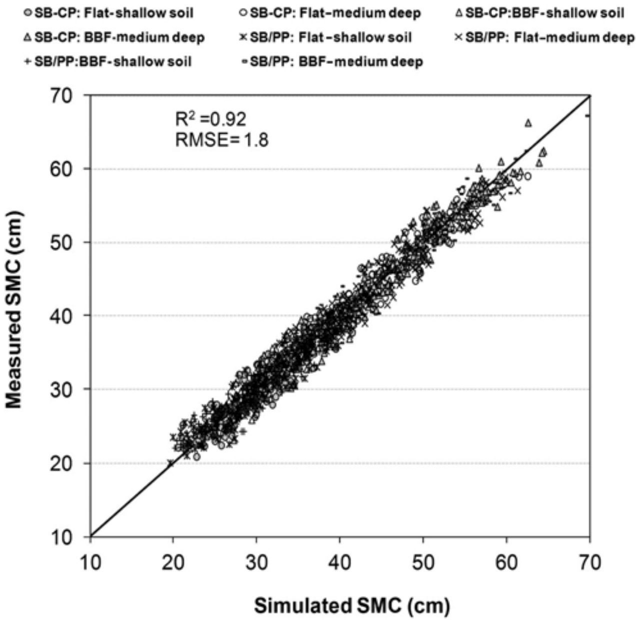

Figure 7. Comparison of the simulated and measured SMC results in BW7 watershed. Data are from eight different treatments between 1996 and 2004.

root system exclusively by the end of the monsoon period and could utilize green water easily from sub-surface layers in post-monsoon period. In sequential cropping, soil moisture in the surface layer played crucial role especially at early growth stage of chickpea crop. Poor soil moisture in the surface layer seriously affected seed germination and establishment of plant roots despite sufficient moisture available in the sub-surface layers.

For model validation, simulated ET well correlated with measured crop yield. In soybean–chickpea sequential cropping system, eight years data for soybean and chickpea were available under two land-form conditions (BBF and flat) and two soil depths (shallow and medium deep); altogether there were 32 data points for each crop. A linear relationship was found between ET (simulated) and crop yield (measured) (Figure 9 *a*, *b*). ET-yield relationship for monsoon crop (soybean) was found positive, except for few data points. The 2001 season

Table 4. Irrigation water requirements, actual irrigation applied, crop yields in farmers' participatory experimental trials at Mota Vadala (Jamnagar), Dharola (Tonk) and Kothapally (Ranga Reddy) during 2011–12

	Water applied by farmers in WIC-trial fields (actual)	Water applied by farmers in WIC-trial fields (actual)	Water applied by farmers in traditionally managed control field as per calendar basis (actual)
Method of irrigation	Drip	Flood	Flood
Mota Vadala, Jamnagar, Gujarat			
Crop grown	Wheat	Wheat	Wheat
Irrigation water (mm)	460	520	950
No. of irrigation	7	6	13
Crop yield (t ha^{-1})	6.3	5.8	5.9
Deep percolation (mm)	80	150	540
Crop grown	Chickpea	Chickpea	Chickpea
Irrigation water (mm)	300	420	580
No. of irrigations (–)	5	6	9
Crop yield (t ha^{-1})	2.2	1.8	1.8
Deep percolation (mm)	50	150	310
Dharola, Tonk, Rajasthan			
Crop grown	Wheat	Wheat	Wheat
Irrigation water (mm)	260	300	410
No. of irrigation	5	4	5
Crop yield (t ha^{-1})	3.5	3.4	3.5
Deep percolation (mm)	10	30	90
Kothapally, Ranga Reddy, Telangana			
Crop grown	Tomato	Tomato	Tomato
Irrigation water (mm)	400	590	700
No. of irrigation	9	8	10
Crop yield (t ha^{-1})	8.7	8.3	8.3
Deep percolation (mm)	20	150	220

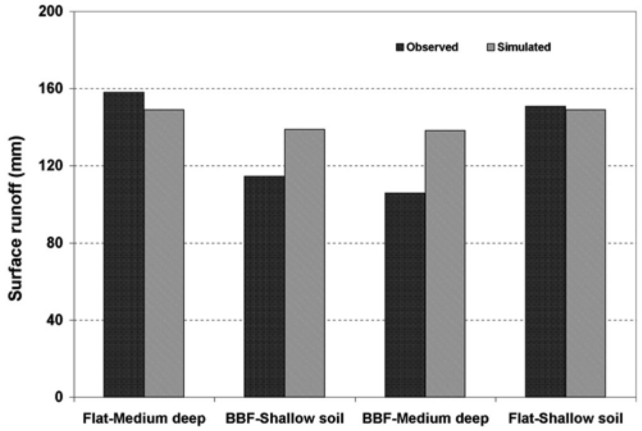

Figure 8. A comparison of surface runoff for different combination of soil depth and land form conditions in BW7 watershed (average over eight-year period between 1996 and 2004).

experienced heavy downpour, which resulted in waterlogging, adversely affecting crop yields. Moreover, ET-yield relationship was found stronger ($R^2 = 0.79$) for chickpea than soybean ($R^2 = 0.65$). Crop grown in the post-monsoon (chickpea) period is mainly dependent on residual soil moisture. Evaporation losses under such situation were relatively less and available moisture in sub-surface layers was mainly utilized through plant transpiration.

Similarly, total biomass yield (grain + straw yield) was correlated with ET for soybean/pigeon pea intercrop. In this system, soybean and pigeon pea crops were sown at the same time, but harvested at different times. Moreover, it is also difficult to compute ET separately for each of these crops. A strong correlation ($R^2 = 0.72$) is found in ET (together for both the crops) and total biomass yield (Figure 9 *c*).

(iii) *Performance of WIC in farmers' fields.* Performance of WIC was evaluated by recommending irrigation scheduling in farmers' fields. Based on minimum WIC inputs on soil type, soil depth, date of sowing and climatic data, exact amount of water on suitable dates was recommended in drip and flood/furrow irrigated fields. Crop yields were compared between WIC and traditionally managed fields. In addition, the measured soil moisture was also compared with the simulated data to assess WIC performance.

(iv) *WIC-based irrigation scheduling and crop yield.* Soils at Jamnagar site are shallow and characterized by poor water holding capacity (Table 2). Frequent irrigation (once in a week) is generally followed in these areas, resulting in 10–14 irrigations for growing wheat and 8–10 irrigations for chickpea crop (Table 4). According to WIC calculation, irrigation frequency and amount was reduced to 30–40% compared to traditionally managed fields. For example, actual water requirement of wheat crop under drip irrigation system was estimated as 460 mm. Moreover, farmers using furrow methods were recommended to irrigate net 520 mm water against 950 mm in control plots (farmers' practice) during 2011–12. This saved 430 mm irrigation water (45% less) compared to the control fields. Similarly, the irrigation requirement for chickpea was estimated 300 mm under the drip system. Farmers using furrow methods were recommended to apply 420 mm water against 580 mm in control fields during 2011–12 (Table 4). This has resulted in 160 mm water saving against the calendar-based water application. Similar to Jamnagar, farmers in Tonk followed the recommended irrigation practices and resulted in 100–150 mm water saving compared to traditionally managed fields as shown in Table 4.

Description of irrigation scheduling for different irrigation methods and its impact on field water balance for selected irrigation scenarios are: (i) WIC-based irrigation scheduling for furrow method; (ii) WIC-based irrigation scheduling for drip method, and (iii) calendar-based irrigation scheduling for furrow method, in selected wheat fields of Jamnagar district during 2011–12 (Figure 10; Table 4). Each scenario (described horizontally) has three vertical panels (i) describing date-wise amount of irrigation applied (shown by bars), available soil moisture for crop use (dotted line) and available soil moisture in 0–60 cm soil profile (smooth line); ii) reference daily crop evapotranspiration demand, ET_0 (smooth line) and actual ET (dotted line); and (iii) cumulative deep percolation from sowing to crop harvesting.

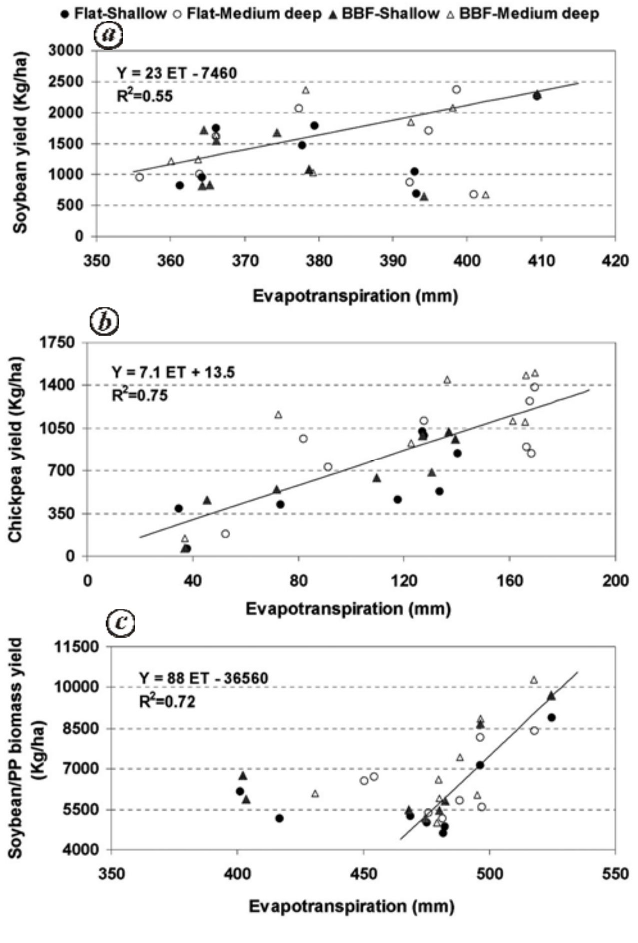

Figure 9. ET (simulated) vs crop yield (measured) relationships developed for soybean–chickpea and soybean/PP system in BW7 watershed (data are from 1996 and 2004).

Irrigation scheduling (time and amount of water to be applied and timing) was found to be largely dependent on irrigation method. At beginning of the crop growth when crop water demand was low, 10–15 mm irrigation at three to five days interval was sufficient which subsequently increased to 30–35 mm at vegetative and grain filling stages in drip-irrigated fields (according to WIC recommendation). For furrow irrigated fields, it was recommended that 20–25 mm water is applied at the beginning of crop growth and 50–80 mm at later stages at five to eight days interval. Additional 30–50% of water application in furrows compared to drip was due to distribution losses (Table 4). On the other hand, 60–80 mm water was consistently applied at weekly interval following the calendar-based protocols under the furrow method. There was significant moisture in 0–60 cm profile but its access for crop use was limited at initial stage due to shorter roots (Figure 10). This moisture was fully utilized when crop roots were developed fully and were able to extract soil moisture from the entire root zone depth.

ET_0 and actual ET of wheat growing season in 2010–11 were shown for respective scenarios (Figure 10). Temperature in Jamnagar reached minimum (max temp: 18–22°C and min temp: 6–10°C) during December and January. ET_0 in December–January was estimated as 2–3 mm day^{-1} which significantly increased to 4–5 mm day^{-1} by the end of the March (max temp 33–37°C and min temp. 18–20°C). Actual ET in the beginning of the crop season was relatively less (<1.5–2 mm day^{-1}) which increased with crop growth. ET at middle of the crop season (after the vegetative stage) was estimated close to ET_0 and declined with crop maturity. Moreover ET after irrigation for one to two days was found close to ET_0 as shown by sharp peaks (Figure 10). Ample amount of moisture in top 10 cm soil was readily available to meet evaporative demand after the water application.

Results further showed that excess irrigation in traditionally managed (control) fields resulted in substantial amount of deep percolation compared to the WIC-managed fields (Table 4 and Figure 10). Deep percolation from drip-irrigated system was almost negligible. Deep percolation losses in WIC-managed fields were reduced by 50–80% compared to calendar-based irrigation (Figure 10).

In addition, despite applying 30–40% less water, yields obtained from WIC-managed fields were comparable with control practice (Table 4). For example, during 2011–12 in Jamnagar, measured average wheat yield from

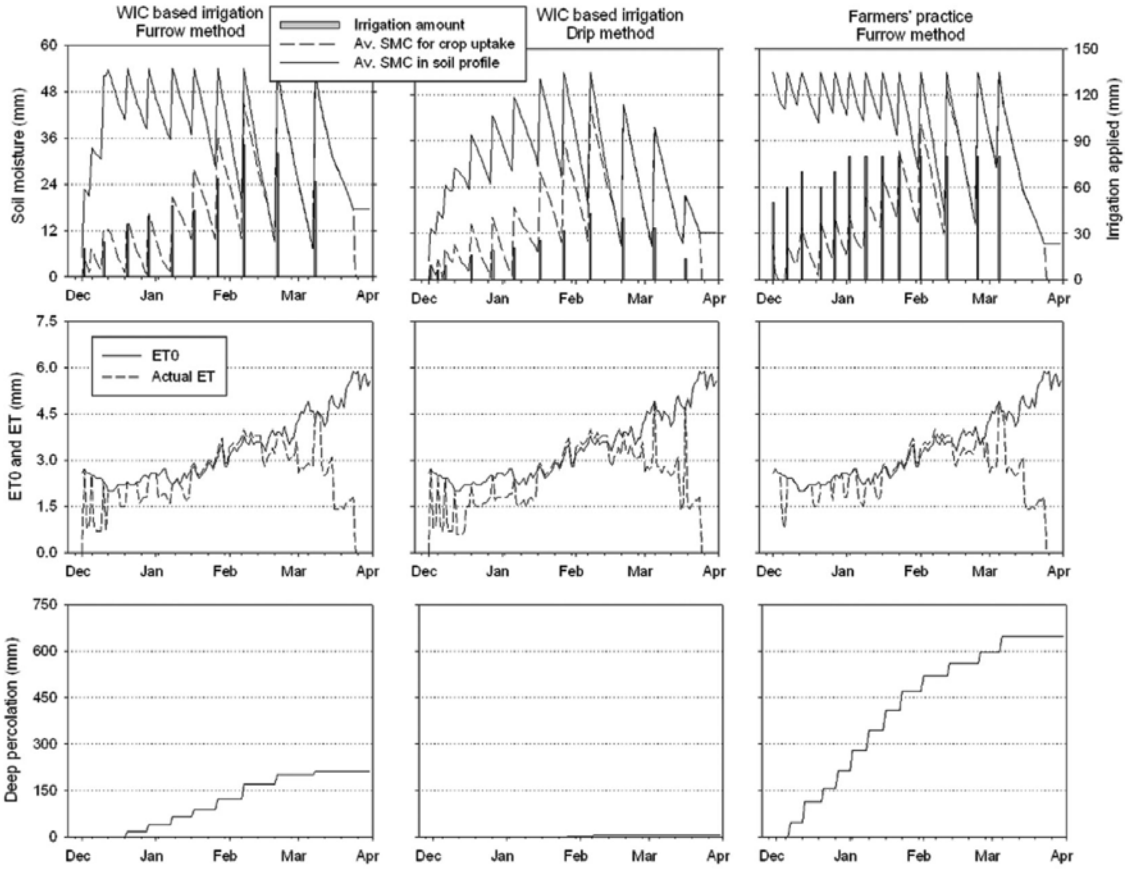

Figure 10. Description of irrigation scheduling for different irrigation methods and its impact on field water balance for selected irrigation scenarios.

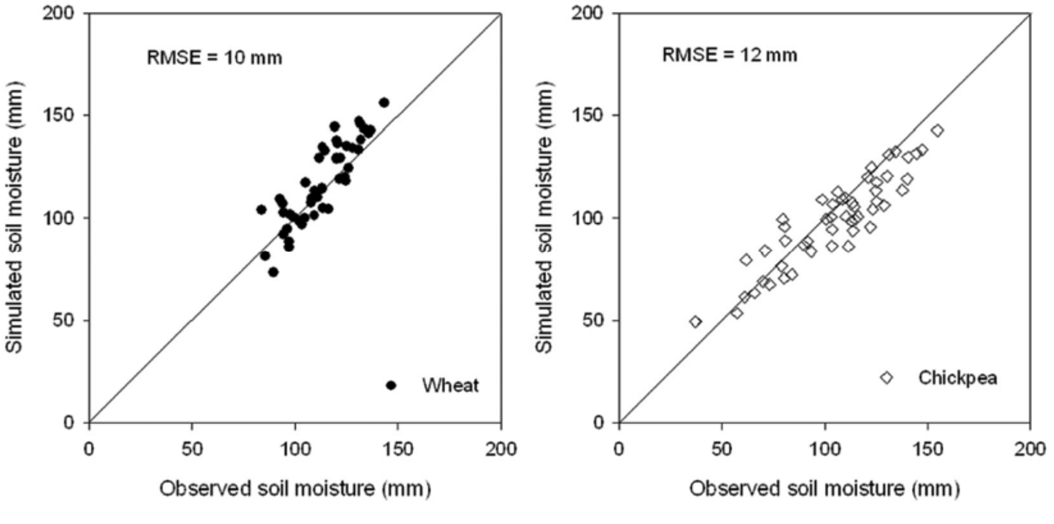

Figure 11. Comparison of simulated soil moisture (0–60 cm depth) results with measured data in selected wheat and chickpea experiment plots at Tonk, Rajasthan during 2010–13.

WIC-recommended plots was 5.8 t ha^{-1} compared to 5.9 t ha^{-1} in calendar-based irrigation plots. Wheat yield was further found to be higher (6.3 t ha^{-1}) under drip irrigation plot which was guided by WIC. Similar results were recorded in different years at various testing sites.

(v) *Soil moisture comparison.* Simulated soil moisture by WIC was in good agreement with the measured soil moisture in farmers' participatory experimental trials. For example, simulated soil moisture of upper 0–60 cm layer was found comparable with the measured soil moisture in selected wheat and chickpea fields during 2010–13 in Tonk (Figure 11). RMSE of WIC in predicting soil moisture was found negligible (i.e. 10–15 mm), which shows technical suitability of WIC in estimating field water balance and further on irrigation scheduling. Similar results were also observed at other sites and also with different cropping systems.

Discussion

Increasing population and growing demand from all sectors including agriculture and changing food diets are making water scarcity a cause of conflict globally. Groundwater plays an important role in India's agriculture as 27 million ha land is covering 55% of total irrigated area depending on it[18]. Decentralized manner of water management provides an excellent opportunity to enhance WUE for bringing sustainability and building resilience in production system as large private investments have been made in groundwater development and its use. Developing countries like India where land holdings are small (<2 ha), farmers are poor and agriculture is characterized by low input uses, enhancing WUE is challenging task. Farmers in the absence of clear guidance generally follow calendar-based irrigation scheduling which results in poor water-use efficiency.

Excel-based farmer-friendly WIC is a simple tool to use which requires user-friendly data. The WIC potentially could be a decision-making tool for small scale field application and farmers can take decision on cropping system and irrigation application. The WIC enables farmer-specific support considering each farmer's field parameters (soil depth, texture, moisture retention) and different land management practices (sowing date and crops) for identifying specific-water based solutions. The WIC enabled to save at least 30–40% water in irrigated area, which currently is channelled through non-productive evaporation and other losses and lead to poor WUE for the farmers during validation phase in three states of India, viz. Rajasthan, Telangana and Gujarat. Moreover, 30% saving in irrigation water would directly reduce the cost of pumping or energy requirements and could save minimum INR 1000–1500 per season per ha.

The present WIC does not consider water ponding and waterlogging situations in field. It is assumed that moisture in soil profile fluctuates between field capacity and permanent wilting point. After rainfall or irrigation application, water gets partitioned quickly in respective soil depths as per defined mass balance approach. Evaporation losses deeper from 10 cm soil depth are considered negligible in WIC. Water, nutrient and temperature stress are important phenomena but their influence on root growth is not considered in the current version. Despite such uncertainty, WIC is proved as simple and powerful decision tool to guide farmers and will be helpful in enhancing food security in dryland areas through enhanced WUE and coping with increasing water scarcity.

Existing simulation tools such as WEAP/CROPWAT are robust, but their uses are limited to scientific community due to complex parameterization. WIC on the other hand is simple in use, requires elementary details and computes water balance according to logical framework. There is no separate installation needed for WIC as it is developed in Microsoft Excel. We targeted important and primary stakeholders like line department officials (e.g. Department of Agriculture, Department of Horticulture, Watershed Department, Command Area Development Authority, land and water resources at the state and national level in India and elsewhere), NGOs and other implementing agencies to use WIC for site-specific water management and irrigation scheduling. Tool could be downloaded from ICRISAT/IDC web-site for their use and providing further feedbacks.

Conclusion

A simple and farmer-friendly WIC was developed to increase WUE in agriculture through a desktop study, tested and validated with strategic research data both at research station and farmers' field. This study primarily focused on developing a simple decision making generic tool to decide the timing and quantity of water to be applied which will be useful for managing water resources by small and marginal farmers of semi-arid tropics. WIC provides important water balance components, i.e. ET, surface runoff, deep percolation, change in soil moisture storages at field and micro-watershed scale. WIC is being tested at both field and watershed scales. Simulated soil moisture content by WIC was found comparable with observed soil moisture content in experimental plots at research station as well as farmers' fields, which is the basis of irrigation scheduling. Water balance made by WIC in these experimental sites clearly showed that calendar-based irrigation scheduling led to large amount of water loss generally due to over irrigation, resulting in poor WUE. Results showed that the number of irrigations and the amount of water applied was reduced by 30–40% using WIC-based irrigation scheduling over the calendar-based method without compensating crop yields.

---

1. Gordon, L. J., Finlayson, C. M. and Falkenmark, M., Managing water in agriculture for food production and other ecosystem services. *Agric. Water Manage.*, 2010, **97**, 512–519.
2. Rockström, J. *et al.*, Managing water in rainfed agriculture. In *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture* (ed. Molden, D. *et al.*), Earthscan, London, UK and International Water Management Institute, Colombo, Sri Lanka, 2007, pp. 315–348.
3. de Fraiture, C., Wichelns., D., Rockström, J. and Kemp-Benedict, E., Looking ahead to 2050: scenarios of alternative investment

approaches. In *Comprehensive Assessment of Water Management in Agriculture, Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture, chapter 3* (ed. Molden, D.), International Water Management Institute, Colombo, Earthscan, London, 2007, pp. 91–145.

4. Khan, S. and Hanjra, M. A., Footprints of water and energy inputs in food production – global perspectives. *Food Policy*, 2009, **34**, 130–140.
5. Hanjra, M. A. and Qureshi, M. E., Global water crisis and future food security in an era of climate change. *Food Policy*, 2010, **35**, 365–377.
6. Wani, S. P., Garg, K. K., Singh, A. K. and Rockstrom, J., Sustainable management of scarce water resource in tropical rainfed agriculture. In *Soil Water and Agronomic Productivity* (eds Lal, R. and Stewart, B. A.), Advances in Soil Science, CRC Press, United Kingdom, 2012, pp. 347–408.
7. FAO, CROPWAT – a computer program for irrigation planning and management, 1992; Online available at http://www.fao.org/nr/water/infores_databases_cropwat.html
8. Falkenmark, M., Land-water linkages – a synopsis, land and water integration and river basin management. *FAO Land Water Bull.*, 1995, **1**, 15–16.
9. USDA SCS, *National Engineering Handbook Section 4. Hydrology*, USDA-SCS, Washington, DC, USA, 1972.
10. Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Williams, J. R. and King, K. W., Soil and water assessment tool, Theoretical documentation, 2005.
11. Hawkins, R., Asymptotic determination of runoff curve numbers from data. *J. Irrig. Drain Eng*., 1993, **119**, 334–325.
12. Thornthwaite, C. W., An approach toward a rational classification of climate. *Geogr. Rev*., 1948, **38**, 55–94.
13. Penman, H. L., Evaporation: An introductory survey, Netherlands. *J. Agric. Sci*., 1956, **1**, 9-29; 87–97; 151–153.
14. Allen, R. G., Pereira, L. S., Raes, D. and Smith, M., Crop evapotranspiration: guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper No. 56, Rome, Italy; United Nations, FAO, 1998.
15. Garg, K. K., Karlberg, L., Barron, J., Wani, S. P. and Rockstrom, J., Assessing impact of agricultural water interventions at the Kothapally watershed, Southern India, *Hydrol. Processes*, 2012, **26**, 387–404.
16. Garg, K. K. and Wani, S. P., Opportunities to build groundwater resilience in the semi-arid tropics. Groundwater National Ground Water Association. *Groundwater*, 2013, **51**, 679–691.
17. Singh, P., Alagarswamy, Pathak, P., Wani, S. P., Hoogenboom, G. and Virmani, S. M., Soybean–chickpea rotation on Vertic Inceptisol I, Effect of soil depth and landform on light interception, water balance and crop yields. *Field Crop Res.*, 1999, **63**, 211–224.
18. Government of India, Final report of minor irrigation watershed management for the twelfth five year plan (2012–2017), Planning Commission, Government of India, New Delhi, 2012.

ACKNOWLEDGEMENTS. We thank the team at the ICRISAT Development Center (IDC) and Resilient Dryland Systems (RDS), ICRISAT, India for collecting and providing historical research data and their support. We are grateful to Sustainable Agriculture Initiative platform for providing research grant for developing WIC during 2010–11. We acknowledge consortium partners, BAIF and DEEP NGOs and farmers for conducting field experiments and collecting research data at Tonk, Ranga Reddy and Jamnagar. Support of Jain Irrigation Private Ltd in installing drip irrigation system in farmers' fields is acknowledged. Funding support for analysing data and preparing manuscript from CGIAR Research Program on Water, Land and Ecosystems are duly acknowledged.

doi: 10.18520/cs/v110/i9/1716-1729