International Water Management Institute

ITC Limited

Drought-Proofing Tool Technical Manual

Innovative water solutions for sustainable development

• Food • Climate • Growth

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Introduction

Drought-proofing tool is developed to operationalize the Drought-proofing framework (Figure 1). In the framework, drought-proofing in a watershed is conceptualized as an interaction between water availability for crop and water productivity or use efficiency. In the framework, 'drought-proofing' is conceptualised as an interaction between water availability for crop (% of crop water need met) and how efficiently available water is used (Figure 1). Across a simple 2*2 plane, we can identify four distinct quadrants with water availability for crop on y-axis and crop water productivity on x–axis. Quadrant 1 is the ideal quadrant where water availability is sufficient to meet crop water needs and available water is used efficiently. In other quadrant, there has to be focus on increasing water availability (quadrant 4) or water use efficiency (Quadrant 2) or both (Quadrant 3). By analysis where watershed crops lies in different rainfall years, user can identify the type and intensity of required interventions. Water availability can be increased with supply augmenting practices (storages, recharge, and soil moisture conservation) whereas water use efficiency can be increased by increasing yield or reducing non-beneficial evaporation and increasing irrigation application efficiency.

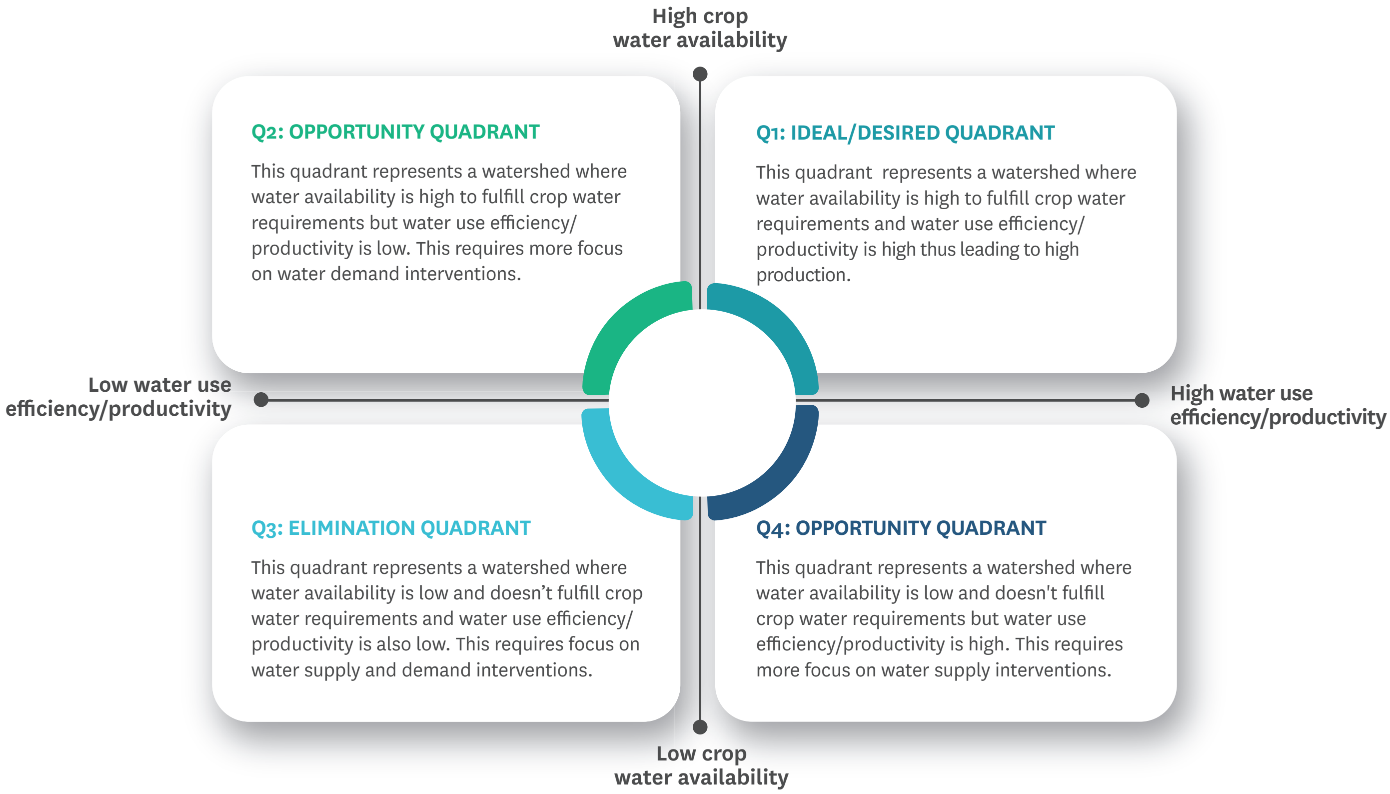
With water as the key input to the drought-proofing framework (Figure 1), a drought-proofing tool is developed to operationalize the framework. Water balance tool helps in site specific water balance, crop yield and crop requirement assessments.

The two key functions of the tool are as follows:

1. To assess water balance of study area under different conditions (dry, normal and wet year)
2. To assess the impact of proposed land and water interventions on water balance for study area.

The water balance results from before and after the interventions are plotted in the same drought -proofing framework plot to monitor the change in crop yield and productivity. The tool is modeled in excel spread sheet with minimum input data requirements for simplifications. This technical manual provides the methodological details and technical details of the backend processes. Steps to prepare input data and run GUI are provided in the user manual.

Figure 1: Conceptual physical drought-proofing framework



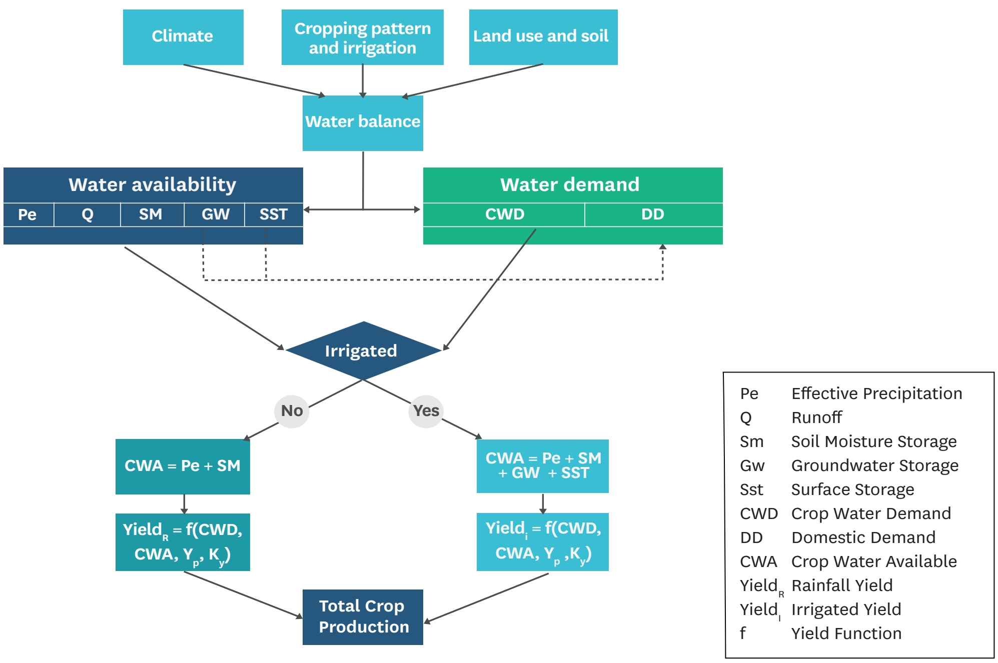
Methodology

Figure 2 gives the conceptual workflow of developed water balance tool processes. The tool applies monthly water balance approach in estimating and balancing water availability and water demand (crop water requirements + domestic water needs) within the study area. Water availability consists rainfall partitioned into effective rainfall (Pe), surface runoff (Q), soil moisture (SM), ground water recharge (GW) and reservoir storage (SST). Water demand consists of crop, domestic and livestock water requirements. Water resource management practices (supply side, demand side and soil moisture interventions) are inbuilt in tool. Management practices alter water balance by changing runoff, recharge, soil moisture and demand. Impact of interventions is translated to increase crop yields (and production) which is monetised using crop prices to get benefit-cost ratio.

The key steps involved in the drought tool are as follows:

- **Step 1:** Enter input data on climate, cropping pattern, land use, soil and irrigation.
- **Step 2:** Calculate water balance components: runoff, recharge, evapotranspiration, soil moisture and reservoir storage for different drought years.
- **Step 3:** Calculate total water availability for agricultural and domestic needs.
- **Step 4:** Calculate crop, domestic and livestock water requirements.
- **Step 5:** Calculate crop water available for rain-fed and irrigated crops. For rain-fed crops, only effective rainfall and soil moisture adds to crop water availability whereas irrigated crops can additionally rely on groundwater and surface storages
- **Step 6:** Calculate crop yield based on the crop water requirement met.
- **Step7:** Simulate impact of water management interventions on water availability and demand.
- **Step 8:** Translate the impact of change in water availability and demand to change in crop yields and benefit-cost ratio.

Figure 2: Water balance tool conceptual workflow



Water Balance Components

Figure 3 gives general conceptual framework and components of water balance. Precipitation is first partitioned into overland runoff (Q_O). Thereafter, effective precipitation ($P-Q_O$) infiltrates and increases soil moisture storage (SM_{ST}). Soil moisture storage (SM_{ST}) maximum water holding capacity is limited by soil field capacity. Soil moisture is depleted through crop and soil evapo-transpiration (ET). ET is constrained by available soil moisture deficit (SMD) which is the difference between max soil storage and current soil moisture storage (SM_{ST}). Any surplus storage above soil moisture water holding capacity is assumed to be natural groundwater recharge (GW_{NR}) adding to aquifer storage (AQ_{ST}). In case water storage interventions are in place, overland runoff (Q_O) can be captured by surface water storages (SW_{ST}) and built groundwater recharge structure capacity (GW_{ST}). Irrigation from surface water (I_{SW}) and groundwater (I_{GW}) adds to evapotranspiration (ET_{SW} and ET_{GW}). In addition, open surface evaporation from surface water storage also adds to ET_{SW}.

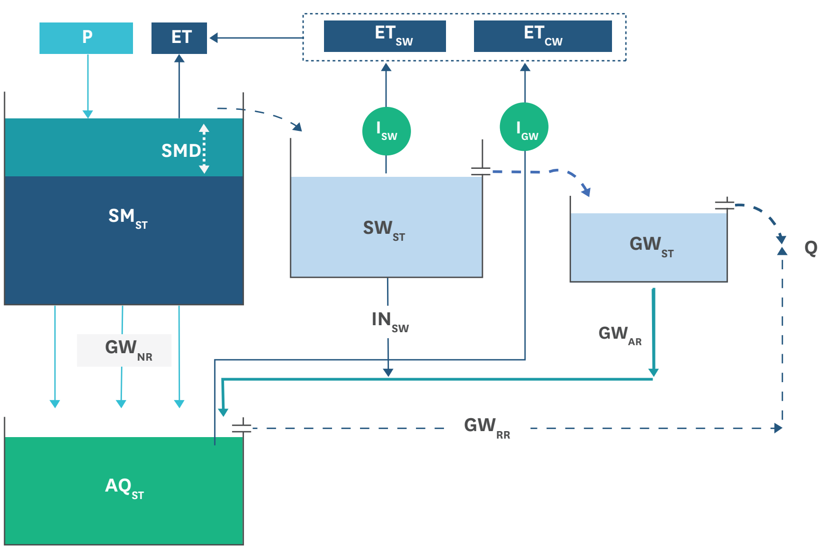
Overland runoff (Q_O) after captured by surface and groundwater storage leaves the watershed, named as total runoff (Q). Infiltration from surface storages (IN_{SW}) and artificial recharge (GW_{AR}) from recharge structures adds to aquifer storage (AQ_{ST}). Maximum storage of aquifer is limited by aquifer depth and specific yield. At the end of day, any surplus storage above maximum storage of aquifer is converted to rejected recharge (GW_{RR}) and added to runoff (Q) leaving the watershed. Overall daily water balance is given by (Eq. 1):

Eq. 1

$$P=Q+ET\pm AQ_{ST}+SM_{ST}\pm SW_{st}$$

Where, P – Precipitation, ET – Evapotranspiration, SM_{ST} – Soil moisture storage, Q – Runoff, AQ_{ST} - aquifer storage and SW_{ST} - Surface water Storage

Figure 3: Conceptual flow of water balance components of the tool



P	Precipitation
Qo	Overland runoff
ET	Evapotranspiration
I_{SW} ET_{SW}	Irrigation and Evapotranspiration from Surface water irrigation
I_{SW} ET_{GW}	Irrigation and Evapotranspiration form groundwater irrigation
SM_{ST}	Soil moisture storage
SMD	Soil moisture deficit
SW_{ST}	Surface water storage
GW_{ST}	Recharge structures storage
AQ_{ST}	Aquifer storage
GW_{NR}	Groundwater natural recharge
IN_{SW}	Infiltration from surface storage
GW_{AR}	Artificial recharge from recharge Structures
GW_{RR}	Groundwater rejected recharge
Q	Runoff leaving watershed

Surface Runoff

Surface runoff is estimated using empirical runoff method of the soil conservations service (SCS curve number method (USDA 1972) which is a simple, stable and robust method. SRC curve number method (USDA 1972) is more suitable for daily time step and doesn't give accurate monthly estimates. With surface runoff controlling effective precipitation (precipitation – runoff), soil moisture storage and in turn groundwater recharge, water balance components is calculated first at daily time step and then aggregated on monthly time scale.

Daily runoff ($Q_{(i)}$) is calculated **(Eq.2)** and then aggregated at monthly level ($Q_{o(m)}$) **(Eq.3)**.

Eq.2

$$Q_{(i)} = \frac{(P_{(i)} - I_a)^2}{P_{(i)} - Ia + S}$$

Eq.3

$$Q_{o(m)} = \Sigma Q_{(i)}$$

Where $Q_{(i)}$ = daily runoff (mm); $Q_{o(m)}$ = total monthly runoff (mm); P_i = daily rainfall (mm); I_a = Initial abstractions (mm) and S= Retention (mm) calculated as a function of Curve number (CN) which is a measure of water retention in the watershed and is calculated as:

Eq.4

$$S_{(i)} = \frac{25400}{CN_{(i)}} - 254$$

Daily CN number ($CN_{(i)}$) was calculated accounting for antecedent moisture conditions (AMC). Initial abstraction (I_a) value of 0.2S is used.

Surface Storage

Part of monthly runoff is captured in surface water reservoirs ($Q_{c(m)}$). Runoff captured is limited by the existing and available storage capacity in each month.

Eq.5

$$Q_{c(m)} = \text{minimum}\ (Q_{O(m)}, SW_{ST(m)})$$

Eq.6

$$SW_{ST(m)} = SST - SW_{ST(m-1)}$$

Where $Q_{O(m)}$ is the total monthly runoff,$Q_{c(m)}$ is the monthly runoff captured in surface reservoirs and $SW_{ST(m)}$ & $SW_{ST(m-1)}$ are the surface water storage available for the current month and previous month respectively and SST is the absolute surface reservoir storage available in the study area. Surface reservoirs lose water though evaporation and infiltration (IN_{SW}). Monthly surface storage of the current month ($SW_{ST(m)}$) is calculated by

Eq.7

$$SW_{ST(m)} = SW_{ST(m-1)} - IN_{SW(m-1)} - ET_{sw(m-1)} - I_{sw(m-1)}$$

Monthly infiltration ($IN_{SW(m)}$) from surface water storage is estimated based on reservoir soil infiltration rate and is added to aquifer storage ($AQ_{ST(m)}$). ET_{sw} is the evapotranspiration from surface water storage (i.e. open surface water evaporation) and ISW is the irrigated water extracted for irrigation and domestic purpose.

Groundwater Recharge Structure

Overland runoff after captured by surface water storage is further captured by groundwater recharge structures, if constructed. Groundwater recharge structure is defined in the tool by their maximum recharge capacity/storage (GW_{ST}). Runoff is recharged by recharge structures ($GW_{AR(m)}$) limited by their recharge capacity (GW_{ST}) and available runoff (Eq. 8).

Eq.8

$$GW_{AR(m)} = \text{minimum}\ (Q_{O(m)} - Q_{c(m)}, GW_{ST(m)})$$

Where $Q_{O(m)}$ is the total monthly runoff, $Q_{c(m)}$ is the monthly runoff captured in surface reservoirs (Eq. 6). Monthly artificial groundwater recharge ($GW_{AR(m)}$) from recharge structure is subtracted from overland runoff and is added to aquifer storage ($AQ_{ST(m)}$).

Soil moisture balance and Evapotranspiration (ET)

Rainfall after overland surface runoff is effective precipitation ($P_{e(i)}$) which infiltrates and adds to soil moisture storage. Soil moisture is depleted through actual soil and crop evapotranspiration. Daily soil moisture balance is calculated using methodology as given in (Rushton, Eilers and Carter 2005).

Eq.9

$$P_{e(i)} = P_{(i)} - Q_{O(i)}$$

Soil storage is calculated in terms of Soil Moisture Deficit (SMD) which gives how much of soil moisture is depleted relative to soil's maximum capacity i.e. field capacity (soil field capacity – soil moisture storage). SMD_i on i^{th} day is calculated as:

Eq.10

$$SMD_{(i)} = SMD_{(i-1)} - ET_{(i)} + Pe_{(i)}$$

$$ET_{(i)} = AE_{soil(i)} - AE_{crop(i)}$$

Where SMD is Soil moisture deficit, $AE_{soil(i)}$ and $AE_{crop(i)}$ are the actual soil evaporation and crop evapotranspiration on the i^{th} day.

Potential and Actual Evapotranspiration

Potential ET

To calculate daily actual evaporation from soil and crop evapotranspiration, first monthly reference evapotranspiration ($ET_{O(m)}$) is determined using Hargreaves method (Hargreaves and Samani 1985). Hargreaves method is an empirical model requiring only monthly average, minimum and maximum temperature along with solar radiation. The monthly reference evapotranspiration ($ET_{O(m)}$) is calculated by,

Eq.11

$$ET_{O(m)} = 0.0022 * R_{A(m)} * \delta'_{T(m)} * (T_{mean(m)} + 17.8)$$

Where:

$ET_{O(m)}$ is the reference evapotranspiration of month (m).

$R_{A(m)}$ is the mean extra-terrestrial radiation of a month (m), which is a function of latitude

$\delta'_{T(m)}$ is the difference between monthly min and max temperature ($T_{max(m)} - T_{min(m)}$)

$T_{mean(m)}$ is the mean temperature of month (m)

m = month (Jan to dec)

Thereafter, reference evapotranspiration at daily time step ($ET_{O(i)}$) is simply calculated by dividing monthly reference evapotranspiration ($ET_{O(m)}$) with number of days in a month ($Days_{(m)}$).

Eq.12

$$ET_{O(i)}=ET_{O(m)}/Days_{(m)}$$

The potential evaporation from soil surface ($ES_{(i)}$) on the i^th^ day is calculated from the reference crop evapotranspiration. $ES_{(i)}$ is calculated at daily time step and then aggregated on monthly time scale. Potential evaporation from soil ($ES_{(i)}$) on i^{th} day is calculated as

Eq.13

$$ES_{(i)}=K_E*ET_{O(i)}$$

where K_E is the evaporation coefficient taken as K_E =1.10 for temperate climates and 1.05 for semi-arid climate.

The potential crop evapotranspiration ($ET_{C(i)}$) on the i^{th} day is calculated using crop coefficient method (Richard, et al. 1998) from the reference evapotranspiration as:

Eq.14

$$ET_{C(i)}=K_{C(i)}*ET_{O(i)}$$

Where, $K_{C(i)}$ is the crop coefficient of the i^{th} day. $K_{C(i)}$ varies across four stages of crop growth (Four stages of crop growth are Initial, development, mid and late stage).

Actual Soil Evaporation

Actual soil evaporation is calculated using improved soil moisture balance method (Rushton, Eilers and Carter 2005). In this method, potential soil evaporation is limited by the available soil moisture storage. Below steps briefly provides the estimation of actual evaporation. Stress coefficient (K'_s) is used to translate the potential to actual evaporation. Stress coefficient depends on:

- Soil moisture deficit (SMD) which indicates how much of soil moisture is depleted relative to soil maximum storage (soil field capacity – soil moisture storage)
- Total Evaporable Water (TEW) which is the maximum total depth of water that can be evaporated from the surface soil layer is calculated by,

Eq.15

$$TEW=1000(\theta_{FC}-0.5*\theta_{WP}) Z_E$$

θ_{FC} is the Field Capacity of soil and θ_{WP} is Permanent Wilting Point, which is the soil moisture content below which plant roots cannot extract moisture. Z_E depth of surface soil layer (Range 0.1m to 0.25m) from which soil evaporation takes place.

- Readily Evaporable Water (REW) which is the maximum total depth of water that can be evaporated during stage 1 when no soil moisture stress exists.

Eq.16

$$REW_{(i)}=p*TEW_{(i)}$$

p is the depletion factor ranging between 0.2 and 0.7.

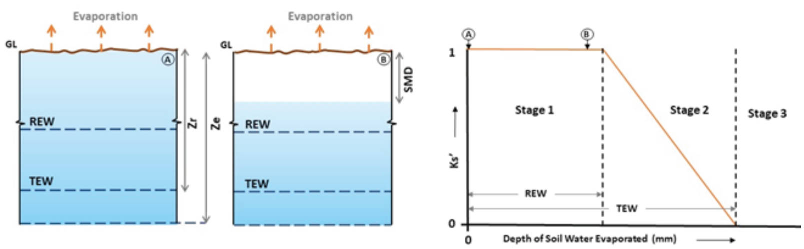
Depending on soil moisture deficit, three stages are defined (Figure 4 a, b &c and Table 1). In the stage 1, soil moisture storage is nearly full and it is assumed that evaporation from soil exposed to the atmosphere will occur at the maximum rate, limited only by energy availability at the soil surface. In stage 2, soil surface is visibly dry and the evaporation from the exposed soil decreases in proportion to the amount of water remaining in the surface soil layer. In the stage 3, no evaporation occurs since Soil Moisture Deficit is greater than Total Evaporable Water.

Table 1: Stages of soil evaporation

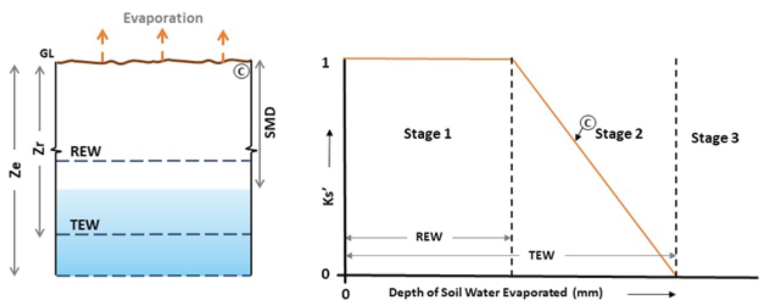
	Description	SMD	Ks’	$AE_{soil(i)}$
Stage 1	Energy Limiting Stage	$SMD_{(i-1)}<REW_{(i)}$	1	$ES_{(i)}$
Stage 2	Falling Rate Stage	$TEW_{(i)}>SMD_{(i-1)}>REW_{(i)}$	$\frac{TEW_{(i)}-SMD_{(i-1)}}{TEW_{(i)}-REW_{(i)}}$	$P_{e(i)}+K'_{s(i)}(E_{S(i)}-P_{e(i)})$
Stage 3	Zero Stage	$SMD_{(i-1)}>TEW_{(i)}$ and $Pe_{(i)}<ES_{(i)}$	0	$P_{e(i)}$

Figure 4: Stage of soil evaporation a) Stage 1, b) Stage 2 and c) Stage 3

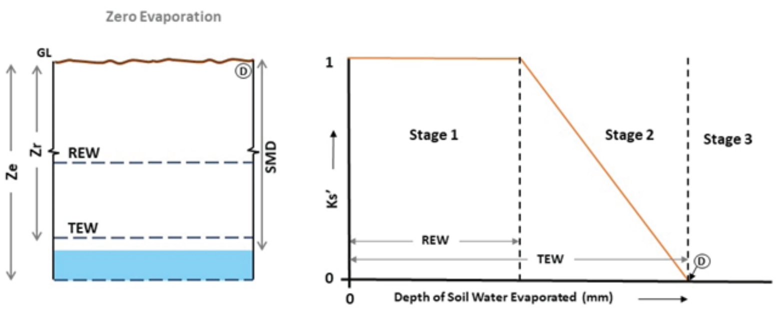
A



B



C



Actual Crop Evapotranspiration

Similarly, crop evapotranspiration is limited by the available soil moisture storage which is calculated using soil moisture balance methodology (Rushton, Eilers and Carter 2005). Below steps provides briefly the estimation of actual crop evapotranspiration. Stress coefficient (Ks) is used to translate the potential to actual evapotranspiration. Stress coefficient depends on:

- Soil moisture deficit (SMD) which indicates how much of soil moisture is depleted relative to soil field capacity (soil field capacity – soil moisture storage)
- Total Available Water (TAW) is the total water available (max field capacity) to plants. Field capacity is the amount of water that a well- drained soil should hold against gravitational forces

Eq.17

$$TAW=1000(\theta_{FC}-\theta_{WP})\ Z_R$$

θ_{FC} is the Field Capacity of soil and θ_{WP} is Permanent Wilting Point, which is the soil moisture content below which plant roots cannot extract moisture. Z_R is the root depth which varies in each growth stage. Soil depth is always greater than or equal to the root depth (i.e.$Z_E>Z_R$).

- Readily available Water (RAW) is fraction of TAW that a crop can extract from the root zone without suffering water stress. RAW on ith is calculated by,

Eq.18

$$RAW_{(i)}=p*TAW_{(i)}$$

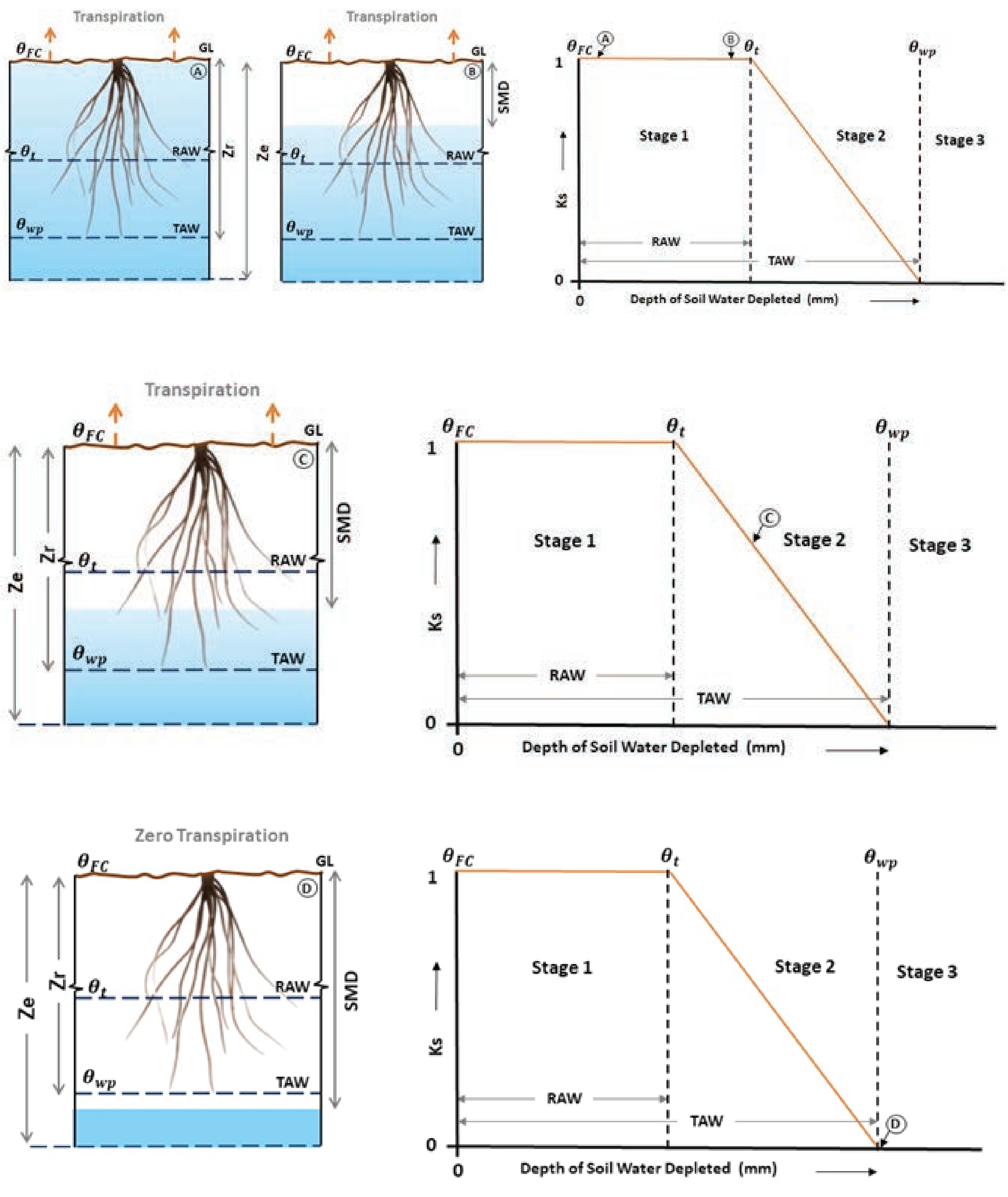
p is the depletion factor ranging between 0.2 and 0.7`

Depending on soil moisture deficit, three stages are defined (Figure 5 a, b & c and Table 2). In the stage 1, soil moisture storage is nearly full and it is assumed that evapotranspiration will occur at the maximum rate. In the stage 2, the evapotranspiration decreases with proportion of total available water (TAW) to the readily available water (RAW). In the stage 3, no evapotranspiration occurs since Soil Moisture Deficit is greater than Total Evaporable Water and infiltration is less than the crop evapotranspiration.

Table 2: Stages of evapotranspiration

	Description	SMD	Ks'	$AE_{Crop(i)}$
Stage 1	Energy Limiting Stage	$SMD_{(i-1)}<RAW_{(i)}$	1	$ES_{(i)}$
Stage 2	Falling Rate Stage	$TAW_{(i)}>SMD_{(i-1)}>RAW_{(i)}$ & $In_{(i)}<ET_{C(i)}$	$\frac{TEW_{(i)}-SMD_{(i-1)}}{TAW_{(i)}-RAW_{(i)}}$	$P_{e(i)}+K_{s(i)}(ET_{C(i)}-P_{e(i)})$
Stage 3	Zero Stage	$SMD_{(i-1)}>TAW_{(i)}$ and $In_{(i)}<ETc_{(i)}$	0	$P_{e(i)}$

Figure 5: Stage of crop evapotranspiration a) Stage 1, b) Stage 2 and c) Stage 3



Groundwater Recharge

Groundwater recharge is assumed to occur on days when the calculation leads to a negative soil moisture deficit ($-SMD_{(i)}$) i.e. soil moisture storage exceeds maximum storage capacity. As the SMD becomes zero, the soil reaches field capacity and becomes free draining. Consequently, recharge.

If $SMD_{(i)}<0$, then groundwater natural recharge ($GW_{NR(i)}$) on i^{th} day is,

Eq.19

$$GW_{NR(i)}=-SMD_{(i)}$$

If $SMD_{(i)}>0$, then groundwater natural recharge ($GW_{NR(i)}$) on i^{th} day is

Eq.20

$$GW_{NR(i)}=0$$

Daily groundwater natural recharge ($GW_{(NR(i)}$) is aggregated on monthly level ($GW_{(NR(m)}$).

Eq.21

$$GW_{NR(i)}=\Sigma GW_{NR(i)}$$

Infiltration ($IN_{SW(m)}$) from surface water storage (Eq. 7) and artificial recharge ($GW_{AR(m)}$) from recharge structures (Eq. 8) is added to aquifer storage and groundwater water extracted for irrigation (I_{Gw})in previous month is subtracted from aquifer storage. The monthly aquifer storage ($AQ_{ST(m)}$) becomes,

Eq.22

$$AQ_{ST(m)}=AQ_{ST(m-1)}+GW_{NR(m)}+IN_{SW(m)}+GW_{AR(m)}-I_{GW(m-1)}$$

At the end of month, aquifer storage above maximum aquifer storage (AST) is converted to rejected recharge ($GW_{RR(m)}$) (Eq. 23). Maximum aquifer storage (AST) is a function of aquifer depth, specific yield and watershed area (Eq. 24).

Eq.23

$$GW_{RR}=AQ_{ST(m)}-AST,\ \text{if}\ AQ_{ST(m)}>AST$$

Eq.24

$$AST=D*S_y*A$$

Where, S_y is the specific yield of the aquifer, D is the depth of aquifer and A is the total watershed area.

Rejected recharge (GW_{RR}) end the month from previous month added to month runoff. Runoff leaving watershed (Q_m) if finally calculated as (Eq 25):

Eq.25

$$Q_m=Q_{o(m)}-Q_{c(m)}-GW_{AR(m)}+GW_{RR(m-1)}$$

Crop and Irrigated Water Requirement

Crop water requirement is the potential crop evapotranspiration of a crop (Eq.14) and estimated as a function of reference evapotranspiration (Richard, et al. 1998). Crop water requirement is calculated using reference evapotranspiration and crop coefficient. Crop coefficient ($K_{C(i)}$), varies across four stages of crop growth (Four stages of crop growth are Initial, development, mid and late stage)(Figure 6). Crop Water Requirement of crop is calculated first at daily time step ($CWR_{C(i)}$) and then aggregated on monthly time scale ($CWR_{C(m)}$).

Eq.26

$$CWR_{C(i)}=K_{C(i)}*ET_{O(i)}=ET_{C(i)}$$

Eq.27

$$CWR_{C(m)}=\Sigma CWR_{C(i)}$$

Rainfed Area

For rain-fed areas, available water is restricted to only effective precipitation (P_e) and soil moisture (S_m). Thus, in rain-fed area Corp Water Requirement met is equal to AE_{crop}. This is translated to crop yield (Steduto, et al. 2012).

Eq.28

$$\left(1-\frac{Y_a}{Y_m}\right)=K_Y\left(1-\frac{ET_a}{ET_m}\right)$$

Where ET_a is the actual evapotranspiration of a crop which is AE_c in this study and Et_c is the potential evapotranspiration which is referred as ETc in this study. Y_m and Y_a are the maximum and actual yields and K_y is a yield response factor representing the effect of reduction in evapotranspiration on yield losses.

Irrigated Area

For irrigated crop, in addition to effective precipitation(P_e) and soil moisture(S_m), irrigation can be done through water stored in surface water reservoirs (SW_{st}) and groundwater. Irrigation water requirement (IWR) is calculated as difference between potential CWR and actual crop evapotranspiration ($AE_{(Crop(m)}$)from Table 5). Monthly Irrigation Water Requirement of a crop ($IWR_{c(m)}$)is calculated by considering irrigation efficiency of the crop (Eq.29).

Eq.29

$$IWR_{c(m)}=(ET_{C(m)}-AE_{Crop(m)})/\eta_c$$

if $IWR_{c(m)}$>0,then Irrigation Water Requirement met for a crop (met $IWR_{c(m)}$) is the minimum of IWR requirement and available irrigation in surface and groundwater storages **(Eq.30)**.]

Eq.30

$$\text{met } IWR_{c(m)}=\min\left(\frac{ET_{C(m)}-AE_{C(m)}}{\eta_c},(GW_{r(m)}+SW_{st(m)})\right)$$

Where η_c is the irrigation efficiency of a crop, ($GW_{r(m)}+SW_{st(m)}$) is the groundwater and surface water storage available which is calculated at monthly time step as the sum of groundwater recharge and water stored in surface reservoirs.

Return flows (%) is calculated by irrigation dependency (SW & GW) weighted average. Return flow ration is calculation based on depth of ground water table and return flow value varies for groundwater and surface water is given in Table 3.

Overall return flow (RF_o) is calculated by,

Eq.31

$$RF_o=\frac{(RF_{c(gw)}*D_{c(gw)})+(RF_{c(sw)}*D_{c(sw)})}{100}$$

Where, $RF_{c(gw)}$ is the return flow of crop which is dependent on ground water and $RF_{c(sw)}$ is the return flow of the crop which is dependent on surface water. $D_{c(gw)}$ and $D_{c(sw)}$ are irrigation dependency of a crop on groundwater and surface water respectively (in %).

Then irrigation efficiency of a crop ($\eta_{c(rf)}$) after considering overall return flows (RFo) of a crop is calculated by,

Eq.32

$$n_{c(rf)}=n_c+((1-n_c)*RF_o)$$

The irrigation efficiency after considering overall return flows of crop ($\eta_{c(rf)}$) replaces normal irrigation efficiency of crop(η_c) in Eq.30.

Table 3: Return flow values

Depth of water table m bgl	Groundwater (%)		Surface water (%)	
	Paddy	Non-Paddy	Paddy	Non-Paddy
<=10	45	25	50	30
11	43.3	23.7	48.3	28.7
12	41.7	22.3	46.7	27.3
13	40	21	45	26
14	38.3	19.7	43.3	24.7
15	36.7	18.3	41.7	23.3
16	35	17	40	22
17	33.3	15.7	38.3	20.7
18	31.7	14.3	36.7	19.3
19	30	13	35	18
20	28.3	11.7	33.3	16.7
21	26.7	10.3	31.7	15.3
22	25	9	30	14
23	23.3	7.7	28.3	12.7
24	21.7	6.3	26.7	11.3
>=25	20	5	25	10

For irrigated area, crop yield is calculated by FAO yield response function (Steduto, et al. 2012) as:

Eq.33

$$\left(1-\frac{Y_a}{Y_m}\right)=K_Y\left(1-\frac{ET_a}{ET_m}\right)$$

Eq.34

$$ET_a = AE_{cm} + IWR_{cm}$$

Where ET_a is the actual evapotranspiration = AE_c + met IWR and ET_m is the potential evapotranspiration = ET_c. Y_m and Y_a are the maximum and actual yields and K_y is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses. Yield is calculated at the end of crop duration by summing up CWR and AE_{crop} and met IWR.

Average yield of crop, aggregating rainfed and irrigated area, is then calculates as area averaged yield of both areas:

Eq.35

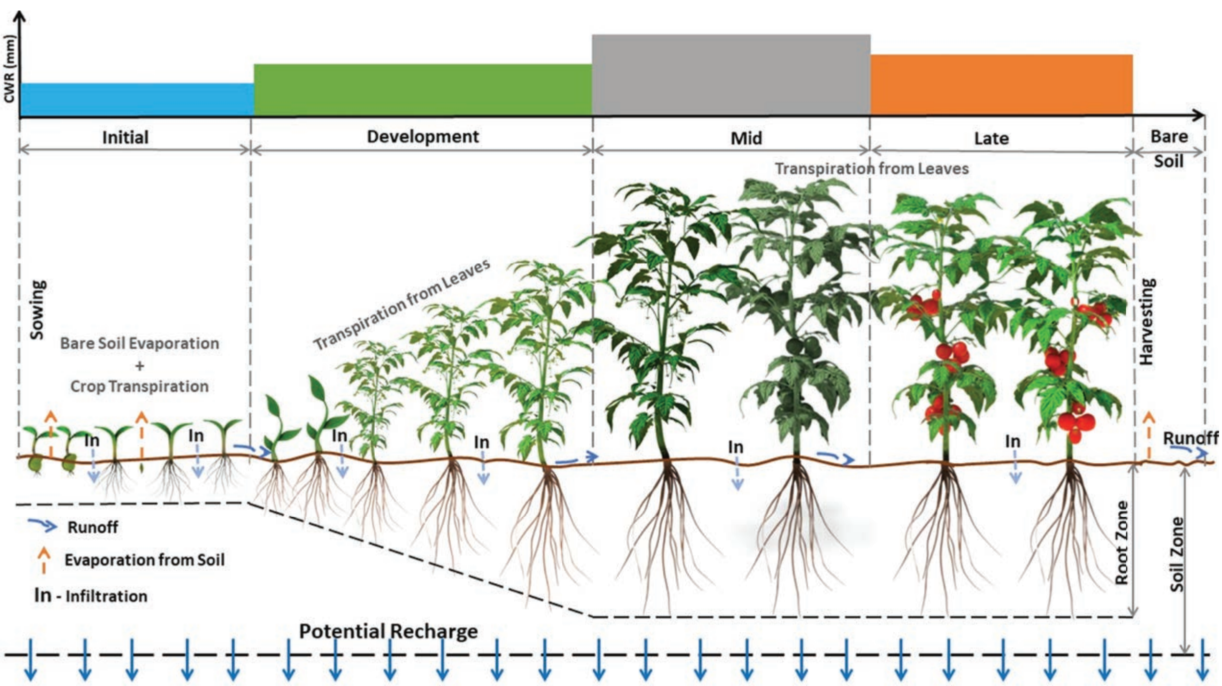
$$Y_{combined,c} = \frac{Y_{rainfed,c} * A_{rainfed,c} + Y_{irrigated,c} * A_{irrigated,c}}{A_c}$$

Note: Comprehensive details for physical processes governing the drought tool are found in Table 3 links.
Details of various parameters involved in physical process is attached in Annexure A.

Table 4: Link to documents for detailed description of physical processes

Physical Process	Authors/ Organization	Applicable in technical manual section	Link	Reference
Runoff	USDA curve number method	Section 3.2	USDA, 1986	(USDA 1972)
Soil moisture and recharge	Ruston et al. 2006	Section 3.3 & 3.4	Ruston et al. 2005	(Rushton, Eilers and Carter 2005)
Reference ET (ETo)	Hargreaves and Samani	Section 3.3	Hargreaves & Samani, 1985	(Hargreaves and Samani 1985)
Crop ET	FAO crop Kc	Section 3.3	FAO, Paper-56	(Steduto, et al.2012)
rop yield	FAO yield response factor	Section 4	FAO, Ky function FAO, Paper-66	(Richard, et al. 1998)

Figure 6: Water Balance Process and Crop Growth stages



Water Management Interventions

Water management interventions are broadly categorised under three categories: Supply side, demand side and soil moisture. They are integrated in the framework by listing and categorising their impact on five physical processes or parameters (Table 5): surface water storage (SW_{st}), groundwater recharge (GW_r), runoff (Q), crop water requirement (CWR) and irrigation water requirement (IWR). Table 6, Table 7 and Table 8 gives the process and rules through which different interventions impact in the tool are integrated. Comprehensive details of interventions are attached in Annexure B.

Table 5: List of physical processes or parameters

Physical process or parameter	How	Rule
Surface water /Reservoir storage (SW_{ST})	Creating physical surface storage ($+SW_{ST}$)	• Captures surface runoff in created storages. • Storage decreases by irrigation, evaporation, and infiltration to groundwater
Groundwater recharge (AR)	Artificial groundwater recharge ($+GW_{AR}$)	• Recharge due to interventions add to monthly recharge and recharge value is updated • Recharge takes place after runoff is captured in reservoirs. • Recharge capacity is defined by infiltration rates and recharge rates.
Overland runoff (Q_O)	Decrease in CN number based on percent of area treated with interventions	• Reduction in surface runoff by interventions is simulated by reducing CN number • Increases infiltration, increasing soil moisture and recharge

Irrigation water requirement (IWR)	Increase in water application efficiency (+η_f) and reduced Irrigation water demand	• Increase in irrigation efficiency reduces irrigation water requirement • Reduced irrigation water demand through agronomy practices is also translated to increased irrigation efficiency.
Crop water requirement (CWR)	Reduces evaporation from bare soil (E%)	• Reduces soil evaporation, which in turn increases the soil moisture. Reduced evaporation is reflected on AE_{soil} calculation.

Supply Side Interventions

Table 6: List of Supply side intervention and associated impact

Intervention	Impact on physical process or parameters	How it works
Farm pond	Increases Storage (+SW_{ST})\ Increases Recharge (+IN_{SW})	Farm pond, Farm Pond (lined) and check dam captures runoff based on overall storage capacity and current storage. Infiltration rate is averaged and is taken out monthly from storage and added to ground water recharge. Recharged water is made available for extraction
Farm pond (Lined)	Provide storage (+SW_{ST})	
Check dam / Gully Plug	Increases Storage (+SW_{ST}) Increases Recharge (+IN_{SW})	
Infiltration Ponds	Increases Recharge (+GW_{AR})	Runoff captured (Volume (m3)) in ponds is added to Ground water recharge through Infiltration. Recharged water is made available for extraction
Injection / Bore wells	Increases Recharge (+GW_{AR})	Recharges runoff directly. Recharged water is made available for extraction

Note: Refer Annexure B for comprehensive details on intervention.

Demand Side Interventions

Table 7: List of demand side intervention and associated impact

Intervention	Impact on physical process or parameters	How it works
Drip Irrigation [Crop Specific]	Increases Water Use Efficiency (+ η)	Irrigation water requirement is reduced due to increased water use efficiency
Sprinkler [Crop Specific]	Increases Water Use Efficiency (+ η)	
Land Levelling [All Crops]	Irrigation water saving (WS in %)	Savings in irrigation water application. Savings in irrigation water application is translated to increased irrigation efficiency.
Direct Seeded Rice (DSR) [Crop Specific]	Irrigation water saving (WS in%)	
Alternate Wetting & Drying (AWD) [Crop Specific]	Irrigation water saving (WS in %)	Savings in irrigation water application. Savings in irrigation water application is translated to increased irrigation efficiency.
System of Rice Intensification (SRI) [Crop Specific	Irrigation water saving (WS in %)	
Ridge & Furrow Irrigation [Crop Specific]	Irrigation water saving (WS in %)	
Deficit Irrigation [Crop Specific]	Irrigation water saving (WS in %)	

Note: Refer Annexure B for comprehensive details on intervention.

Soil Moisture Interventions

Table 8: List of soil moisture intervention and associated impact

Intervention	Impact on physical process or parameters	How it works
Cover Crops [Crop Specific]	Reduces evaporation and runoff (CN Reduction)	Reduces soil evaporation, which in turn increases the soil moisture. Reduced evaporation is reflected on AE_{soil} calculation. Runoff Reduced is added to Groundwater Recharge. (Change in CN number is reduced in Crop wise CN number calculation)
Mulching [Crop Specific]	Reduces evaporation and runoff (CN Reduction)	

Intervention	Impact on physical process or parameters	How it works
Conservation Tillage [All Crops]	Reduces evaporation (E%) and runoff (CN Reduction)	
Tank Desilting [All Crops]	Reduces evaporation (E%) and runoff (CN Reduction)	
Bunds (Field/ Contour bunds) [All Crops]	Reduces Runoff (CN Reduction)	Runoff reduced due to CN reduction. Runoff Reduced is added to Groundwater Recharge. (Change in CN number is reduced in Crop wise CN number calculation) Default CN Reduction - 3
Broad Bed Furrows (BBF) [Crop Specific]	Reduces Runoff (CN Reduction) and Increases Water Use Efficiency (+ η)	Reduces runoff and helps preserve soil moisture for longer periods. Runoff Reduced is added to Groundwater Recharge. (Change in CN number is reduced in Crop wise CN number calculation) Default CN Reduction – 3 Irrigation water requirement is reduced due to increased water use efficiency

Note: Refer Annexure B for comprehensive details on intervention.

Impact of Interventions

Storage and Recharge

Storage and recharge interventions adds to surface storage (SW_{ST}) and groundwater recharge capacity (GW_{ST}), respectively. They increase surface storage (SW_{ST}), infiltration to groundwater (IN_{SW}) and artificial recharge to groundwater (GW_{AR}) (see Eq.5 to Eq.8).

Curve Number (CN_{new})

Soil moisture interventions reduces the runoff (i.e. curve number (CN) is reduced based on the interventions). Curve Number 2 (CN_2) is calculated first, then based on the AMC condition, Curve Number 1(CN_1) or Curve Number 3(CN_3) is calculated (USDA, 1972). Curve Number is calculated on daily time step. The reduction in curve number caused by each intervention is calculated-based on area weighted average of crops with interventions,

Eq.36

$$\Delta CN_{2R,cwi} = \frac{1}{A_{cwi}} \sum_{C=1}^{9} \Delta CN_{2\,R(n)} {*} A_{cwi(n)}$$

Where, $\Delta CN_{2R,cwi}$ is the total CN_2 reduction for crop areas with soil moisture interventions. $\Delta CN_{2\,R(n)}$ is the CN2 reduction due tonth intervention, $A_{cwi(n)}$ is the intervention area of the n^{th} intervention, A_{cwi} is the total crop area with soil moisture interventions.

CN_2 of crops with interventions is calculated.

Eq.37

$$CN_{2,cwi} = CN_{2,a} - CN_{2R,cwi}$$

Where, $CN_{2,cwi}$ is the curve Number of crop area with soil moisture interventions, $CN_{2,a}$ is the actual curve number and $\Delta CN_{2R,cwi}$ is the reduction in curve number due to soil moisture interventions. New CN is calculated-based on area weighted average of crops with interventions and without interventions. Curve Number 2($CN_{2,new(i)}$) on i^{th} day is calculated by,

Eq.38

$$CN_{2,new(i)} = \frac{CN_{2,cwi} {*} A_{cwi} + CN_{2,woi} {*} A_{woi}}{A_{total}}$$

here, $CN_{2,new(i)}$ is the new curve number 2 on the i^{th} day, $CN_{2,woi}$ is the Curve Number of crop area without interventions, A_{cwi} is the crop area with soil moisture interventions, A_{woi} is the crop area without soil moisture interventions, A_{total} is the total crop area ($A_{total}=A_{cwi}+A_{woi}$).

Now Curve Number 1($CN_{1,new(i)}$) on ith day is calculated by,

Eq.39

$$CN_{1,new(i)} = \frac{\Delta CN_{2,new(i)}}{(2.281-0.01281 {*} CN_{2,new(i)})}$$

Eq.40

$$CN_{3,new(i)} = \frac{\Delta CN_{2,new(i)}}{(0.427+0.00573 {*} CN_{2,new(i)})}$$

Depending on the AMC condition, $CN_{1,new(i)}$, $CN_{2,new(i)}$ or $CN_{2,new(i)}$ is used. The newly calculated curve number replaces old curve number $CN_{(i)}$ in Eq.4 in surface runoff calculation.

Irrigation Efficiency and Water Saved Calculation

Demand interventions mainly increase the water use efficiency and saves water. Water use efficiency due to drip, sprinkler and BBF irrigation is calculated based on area weighted average of crops with demand side interventions

Eq.41

$$\Delta CN_{cwi} = \frac{1}{A_{cwi}} \sum_{n=1}^{3} \eta_{c(n)} {*} Ac_{cwi(n)}$$

Where, η_{cwi} is the irrigation efficiency of crop area with interventions (drip, sprinkler and BBF), $\eta_{c(n)}$ is the water use efficiency of the n^{th} intervention (n=1 to 3), $A_{cwi(n)}$ is the intervention area of the n^{th} intervention, A_{cwi} is the total crop area with interventions (drip, sprinkler and BBF).

New irrigation efficiency (η_c) of crop is calculated-based on area weighted average of crops with interventions and without interventions

Eq.42

$$\eta_{c(new)} \quad \frac{\eta_{cwi} {*} A_{cwi} + \eta_{woi} {*} A_{woi}}{A_{total}}$$

Where, η_{woi} is the overall irrigation efficiency of crop area without demand side interventions,

A_{woi} is the crop area without demand side interventions, A_{total} is the total crop area ($A_{total}=A_{cwi}+A_{woi}$)

Demand side interventions that saves water (%) is calculated by area weighted average,

Eq.43

$$WS_{cwi} = \frac{1}{A_{cwi}} \sum_{n=1}^{6} ws_{c(n)} {*} A_{cwi(n)}$$

Where, WS_{cwi} is the overall irrigation water saved (%) in crop area with demand side interventions, $WS_{c(n)}$ is the irrigation water saved due to n^{th} intervention (n=1 to 6) of crop, $A_{cwi(n)}$ is the intervention area of then nth intervention, A_{cwi} is the total crop area with demand side interventions.

Total irrigation water saved of a crop ($WS_{c(total)}$) is calculated based on the area weighted average

Eq.44

$$WS_{c(total)} = \frac{WS_{cwi} {*} A_{cwi} + WS_{woi} {*} A_{woi}}{A_{total}}$$

A_{woi} is the crop area without demand side interventions, A_{total} is the total crop area ($A_{total}=A_{cwi}+A_{woi}$).

Then irrigation efficiency ($\eta_{c,ws}$) of a crop after considering overall water saved ($WS_{c(total)}$) is calculated by

Eq.45

$$\eta_{c(ws)} = \eta_{c(new)} + ((1-\eta_{c(ws)}) {*} WS_{c(total)})$$

The final irrigation efficiency ($\eta_{c(final)}$) of a crop is calculated by combining the new irrigation efficiency ($\eta_{c(new)}$) of a crop and total irrigation water saved (WS_{total}) for a crop. The final irrigation efficiency ($\eta_{c(final)}$) of a crop is calculated by

Eq.46

$$\eta_{c(final)} = \eta_{c(ws)} + (1-\eta_{c(ws)}) {*} RF_o)$$

The final irrigation efficiency ($\eta_{c(final)}$) of a crop replaces normal irrigation efficiency (η_c) of a crop in Eq.30 in Crop Water Requirement calculation.

Evaporation Reduction calculation

Evaporation (E%) due to cover crops, mulching, conservation tillage and tank desilting is calculated based on area weighted average of crops with soil moisture interventions

Eq.47

$$E\%_{cwi(i)} = \frac{1}{A_{wi}} \sum_{n=1}^{4} E\%_{(n)} * A_{cwi(n)}$$

Where, $E\%_{cwi(i)}$ is the overall evaporation of crop area with soil moisture interventions on the i^{th} day, $E\%_{(n)}$ is the evaporation due the n^{th} intervention (n=1 to 4), $A_{cwi(n)}$ is the intervention area of the nth intervention, A_{cwi} is the total crop area with soil moisture interventions (cover crops, mulching, conservation tillage and tank desilting).

New evaporation reduction ($E\%_{new(i)}$) is calculated based on area weighted average of crops with interventions and without interventions

Eq.48

$$E\%_{new(i)} \quad \frac{E\%_{cwi(i)} * A_{cwi} + E\%_{woi(i)} * A_{woi}}{A_{total}}$$

where, $E\%_{new(i)}$ is the new evaporation reduction on the i^{th} day, where $E\%_{woi(i)}$ is the overall evaporation of crop area with soil moisture interventions on the i^{th} day, A_{cwi} is the crop area with interventions, A_{woi} is the crop area without soil moisture interventions, A_{total} is the total crop area ($A_{total}=A_{cwi}+A_{woi}$).

Then Actual Evaporation from soil ($AE_{soil(i)}$) on i^{th} day is calculated by

Eq.49

$$AE_{soil(i)} = AE_{soil(i)} * E\%_{new(i)}$$

During the crop development stage, the evaporation from the soil will be more due to less leaf cover.

Economic Analysis

In economic analysis, Investment, benefits and Benefit-Cost Ratio (BCR) is calculated. Total cost and benefits are calculated to arrive at benefit cost ration (BCR). Investment is total investments of a scenario, which includes maintenance cost.

Total investment for supply side intervention is calculated by

Eq.50

$$Investment_{supply} = \sum_{n=1}^{5} (Volume_n * C_n) + ((Volume_n * C_n) * MC_n)$$

$Volume_n$ is the volume of the nth intervention (n=1 to 5), C_n is the cost per unit volume, MC_n is the maintenance cost of the nth intervention (n=1 to 5)

Total investment for demand side and soil moisture intervention is calculated by

Eq.51

$$Investment_{D+S} = \sum_{n=1}^{14} (Area_n * C_n) + ((Area_n * C_n) * MC_n)$$

$Area_n$ is the area of the n^{th} intervention (n=1 to 14), C_n is the cost per unit area, MC_n is the maintenance cost of the n^{th} intervention (n=1 to 5)

Total investment over 20-year period is calculated by

Eq.52

$$Investment_{total} = Investment_{supply} + Investment_{D+S}$$

For benefits, crop yield increase is converted to absolute yield increase by taking potential attainable yield. Absolute yield increase is converted to monetary values using crop prices (per ton) and crop area under cultivation. Benefits are calculated for each crop separately and aggregated into total benefits. Benefits are calculated based on crop yield increase due to intervention relative to crop yield without interventions.

Eq.53

$$\text{Benefits} = \sum_{n=1}^{9} (Y\%_{c,woi} - Y\%_{c,cwi}) * (Y_{c,p*} Area_c * C_n)$$

Net Present Value (NPV) for investment and benefits is calculated by

Eq.54

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t}$$

NPV of investments and benefits is calculated over time period, t (t=20 years) and discount rate r (6 to 10%). The NPV for investment is calculated by

Eq.55

$$NPV_{investment} = \left(1 - \frac{1}{(1+r)^\wedge t}\right) * \left(\frac{Investment_{total}}{r}\right)$$

The NPV for benefits is calculated by

Eq.56

$$NPV_{benefits} = \left(1 - \frac{1}{(1+r)^\wedge t}\right) * \left(\frac{benefits}{r}\right)$$

Finally Benefit-Cost Ratio (BCR) is calculated by

Eq.57

$$BCR = (NPV_{benefits}) \,/\, (NPV_{investment})$$

Annexure A:
Data sources for components of physical parameters

	Impact on physical process	Where in database	Database Link	Reference
CN number	Runoff (Q)	USDA (Table 2.2a)	USDA, 1986	(USDA 1972)
Hydrological Soil Group	CN number	USDA (Appendix A)	USDA,	(USDA 1972)
Crop Cover Type	CN number	USDA (Table 2.2a)	USDA, 1986	(USDA 1972)
Rainfall and Temperature	Reference Evapotranspiration (ETo) and Runoff (Q)	IMD, Pune	IMD 1, Pune IMD 2, Pune	(IMD n.d.)
Crop coefficient values (Kc)	Crop Evapotranspiration (ETc)	GCWM (Table 2) or FAO (Table 12)	GCWM, 2008 FAO, Paper-56	(IMD n.d.)
Different stage duration	Crop Evapotranspiration (ETc)	GCWM (Table 2) or FAO (Table 11)	GCWM, 2008 or FAO, Paper-56	(Siebert and Doell 2008) (Richard, et al. 1998)
Yield response factor (Ky)	Crop Yield	FAO (Table 1)	FAO, Ky function	FAO, Paper-66 (Steduto, et al. 2012)
Infiltration	Recharge	FAO (Table 7)	FAO, Manual-5	(C. Brouwer, et al. n.d.)
Rooting depth	Soil Moisture	GCWM (Table 2) or FAO (Table 22)	GCWM, 2008 or FAO, Paper-56	(Siebert and Doell 2008) (Richard, et al. 1998)
Crop Depletion Factor	Soil Moisture	GCWM (Table 2) or FAO (Table 22)	GCWM, 2008 or FAO, Paper-56	(Siebert and Doell 2008) (Richard, et al. 1998)
Crop Yield	Crop Yield	Agriculture Statistics (2018), Ministry of Agriculture & Farmers welfare, India	MoAFW, 2018	(MoAFW 2018)
Return Flows	Efficiency	GEC Report, Ministry of Water Resources, River Development & Ganga Rejuvenation, GOI.	MoWRRDGR, 2015	(MoWR 2015)
Aquifer Specific Yield (S_y)	Aquifer Capacity	GEC, Report (2015)	GEC, 2015	(MoWR 2015)

Annexure B:
Intervention data sources

Intervention	Value Range	Database	Database Link	Reference
Drip Irrigation [Crop Specific]	Default Efficiency (η)of 90%	FAO, Annexure 1, Training manual-4 (or)	FAO, Manual-4 TNAU	(Brouwer, Prins and Heibloem 1989) (TNAU n.d.)
Irrigation Management, TNAU. Sprinkler [Crop Specific]	Default Efficiency (η) of 75%	FAO, Annexure 1, Training manual-4 (or) Irrigation Management, TNAU.	FAO, Manual-4 TNAU (TNAU n.d.)	(Brouwer, Prins and Heibloem 1989)
Land levelling [All Crops]	Default irrigation water saved (25 to 30%)	Land levelling, Cultivation Practices, TNAU	TNAU	(TNAU n.d.)
Direct Seeded Rice (DSR) [Rice specific]	Default irrigation water saved (12 to 35%)	DSR-Advance in Agronomy, IRRI	IRRI-CSISA	(Kumar and Ladha 2011)
Alternate Wetting and Drying (AWD) [Rice Specific] for clean development mechanism	Default irrigation water saved (25%)	TNAU, IRRI – (AWD in Philippine Rice Production – Feasibility Study	IRRI-TNAU	(Joel, Siopongco and Sander 2013)
System of Rice Intensification (SRI) [Crop Specific]	Default irrigation water saved (50%)	Expert System for Paddy, Rice ecosystem, TNAU (or) SRI Practices, CFIAD	TNAU CFIAD, Cornell	(TNAU n.d.)
Ridge and Furrow Irrigation [Crop Specific]	Default irrigation water saved (20 to 30%)	Water Management Technology Options for Non-Rice Crops, TNAU	TNAU	(TNAU n.d.)
Deficit Irrigation [Crop Specific]	Default irrigation wate r saved (30%)	Expert System for Paddy, Water management, TNAU	TNAU	(TNAU n.d.)
Farm Pond, Check dams, infiltration ponds, Injection wells- Infiltration value	Depends on soil type and maintenance	Infiltration Rate – Manual on I nfiltration ponds design WDOE, 2003)	WSDOT, 2003	(Massman 2003)
Cover Crops, Mulching, Conservation tillage, Tank	CN reduction value (-2 to -3)	Representation of agricultural conservation practices with SWAT	Purdue, 2007	(Mazdak, et al. 2007)

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