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(ECWS-5)

Soil-water dynamics in flood irrigated orange orchard in central India: Integrated approach of sap flow measurements and HYDRUS 1D model

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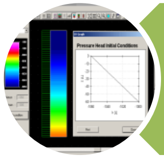
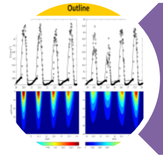
Set up by an Act of Parliament, An Institute of National Importance

Outline

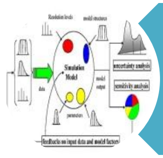
Genesis of the Study



HYDRUS Model Set-up



Validation of HYDRUS Model



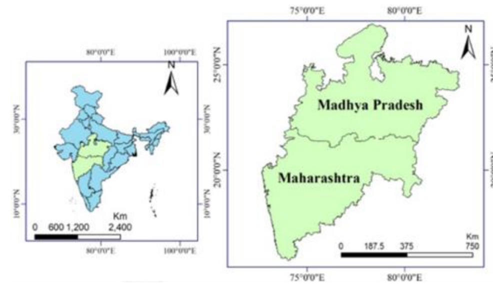
Sensitivity Analysis

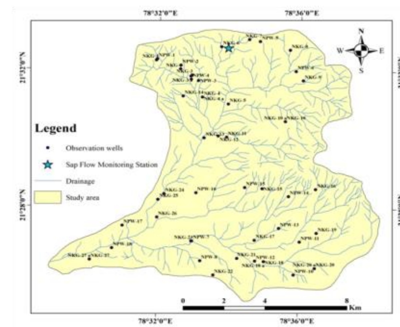
Irrigation Schedule

Conclusion

Genesis of the Study

- The N-P CZO is intensively managed watershed
- 60% land utilised for agri-horticulture
- Extensive use of GW for irrigation of orange orchards
- Watershed is under overexploited condition (GW stage development >100 %)





15-year old mature tree-Water usage, guidelines and practice (Liters/day)		
Measured Water Uptake (Sap flow method)	NHB, Govt. of India	Present Irrigation
5.6	60-170	700

Exorbitantly High

HYDRUS 1D model

- ✓ Assessment of water loss due to evaporation and deep drainage in the present scenario
- ✓ Understanding pattern of root water uptake
- ✓ Sensitivity analysis of the parameters
- ✓ Optimization of irrigation schedule

HYDRUS-1D Model Equations

Richards Equation for water flow and root water uptake in variably saturated soil:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[k\left(\frac{\partial h}{\partial z}+1\right)\right] - \mathrm{S(z,t)}$$

The sink term can be defined as:

$$\mathrm{S(h)} = \alpha(h)\frac{\mathrm{b}'(\mathrm{z})}{\int_0^{\mathrm{L_r}}\mathrm{b}'(\mathrm{z})\mathrm{dz}}\mathrm{T_p}$$

Relationship between θ and h, and K and θ

(van Genuchten-Mualem 1980):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases}$$

$$K(h) = K_s\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^l\left\{1-\left\{1-\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\frac{1}{m}}\right\}^m\right\}^2$$

θ = Volumetric soil-water content [L^3L^{-3}]

h = Soil-water pressure head [L]

k = Unsaturated soil hydraulic conductivity [LT^{-1}]

z = The spatial coordinate (positive upward) [L]

t = Time [T]

S = Sink term [$L^3L^{-3}T^{-1}$]

$\alpha(h)$ = Dimensionless function ($0 \leq \alpha \leq 1$)

L_r = Rooting depth [L]

$b'(z)$ = Root distribution function [L^{-1}]

T_p = Potential transpiration rate [LT^{-1}]

θ_r = residual water content

θ_s = saturated water content

α = inverse of the air-entry value (or bubbling pressure)

n = pore-size distribution index

K_s = saturated hydraulic conductivity

l = pore-connectivity parameter, and $m = 1 - 1/n$ and $n > 1$

HYDRUS-1D model Setup

Geometry Information

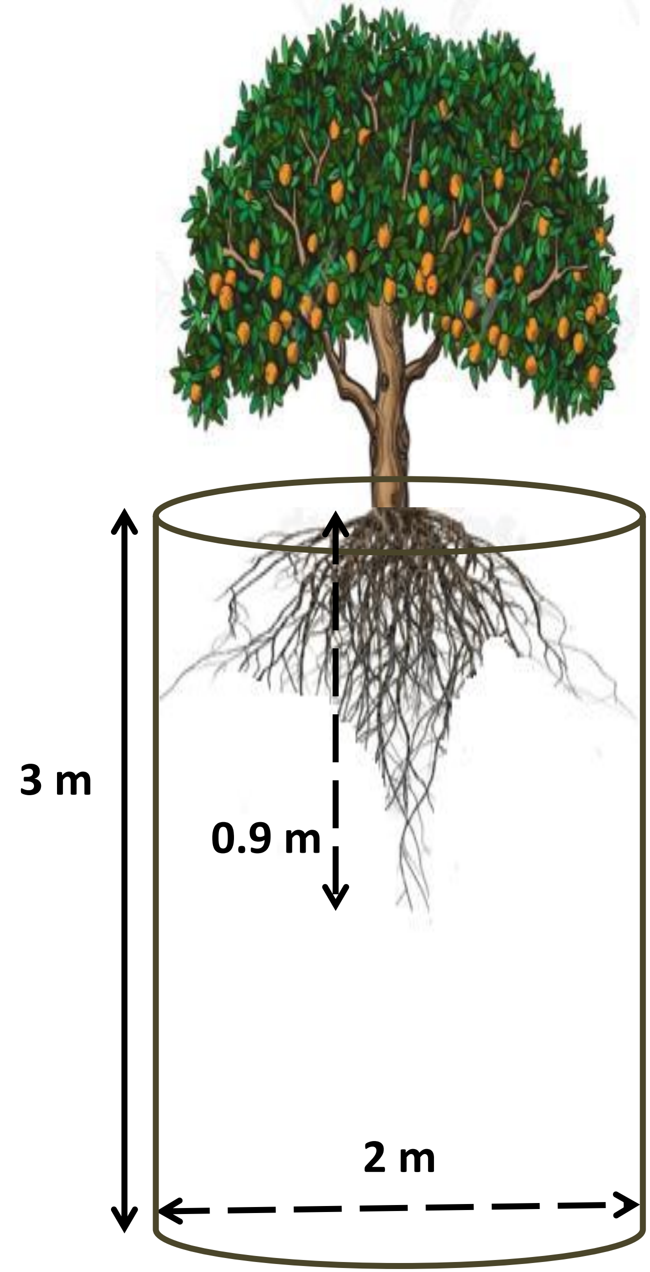
- **Number of Soil Material:** 01
- **Depth of Soil Profile:** 3 m

Model Selection

- **Soil Hydraulic Model: van Genuchten-Mualem**
- **Root Water Uptake Model: Feddes**

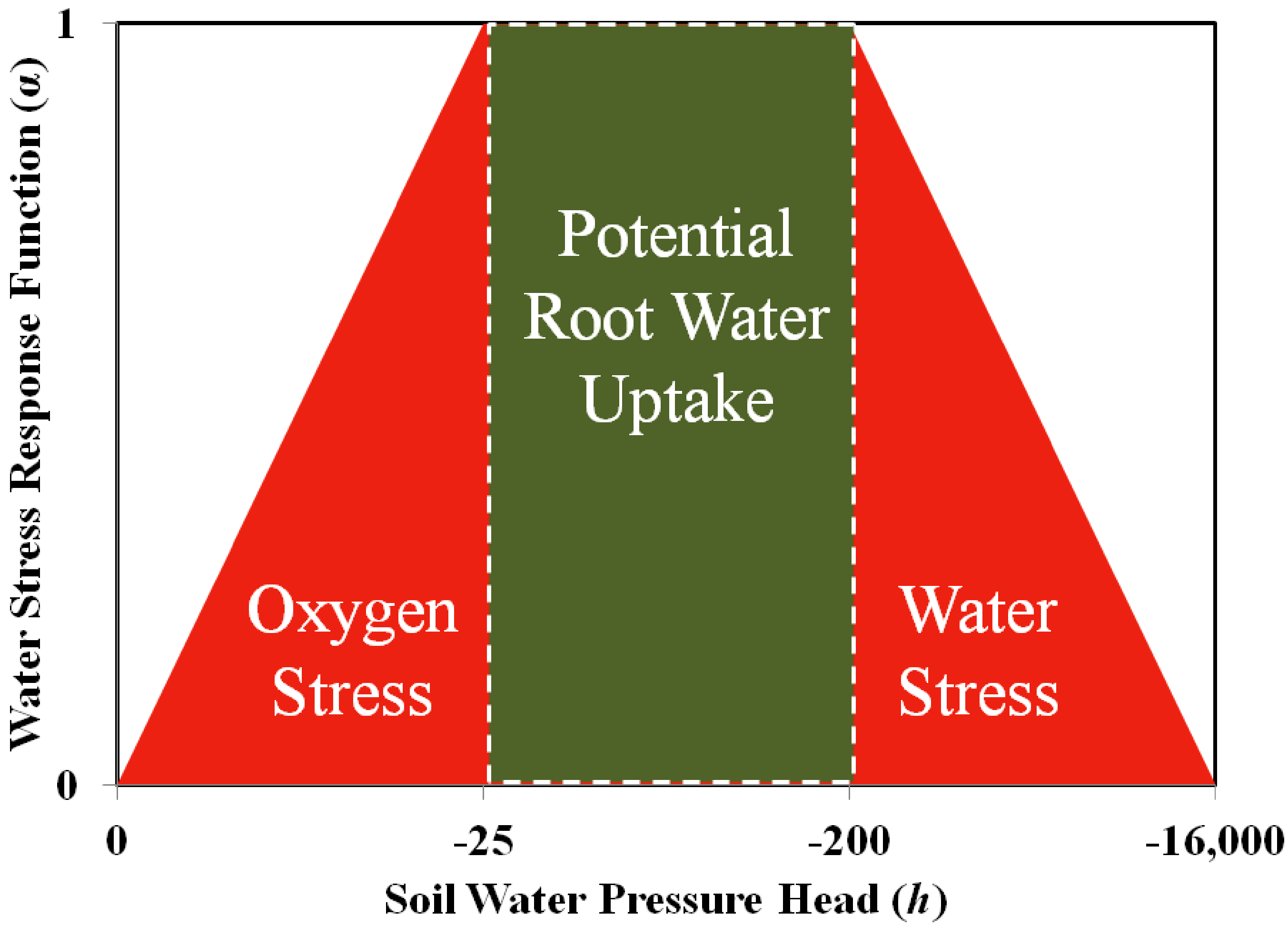
Simulation Period: 61 days

- **4 wet periods (04 days each)**
- **3 dry periods (15 days each)**



HYDRUS-1D model Setup

Feddes Curve for Orange Tree



HYDRUS-1D model Setup

Estimation of Soil Hydraulic properties

- **Soil Hydraulic properties:** Estimated in **HYDRUS 1D** by using **soil texture data***
- The soil texture of the study site **(clay: 60%, silt: 25% and sand 15%)†**

* Rosetta Dynamically Linked Library (DLL)

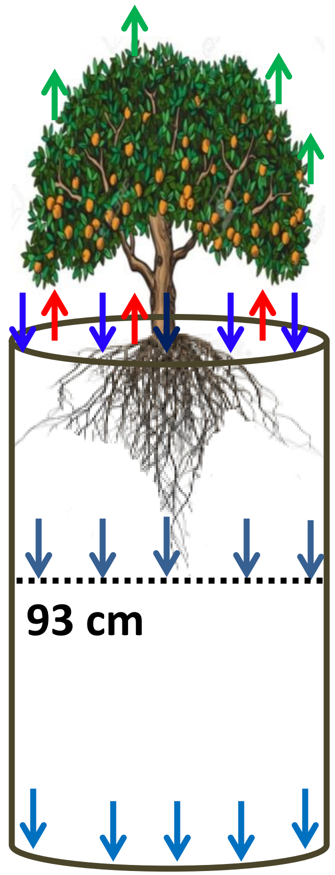
† Soil sample was collected from 15 cm below ground and Texture Analysis was done in Lab

Soil Hydraulic Parameter	Units	Value
Saturated hydraulic conductivity (K_s)	cm d^{-1}	21.12
Saturated soil water content (θ_s)	-	0.4957
Residual soil water content (θ_r)	-	0.0992
The inverse of the air-entry value (or bubbling pressure) (α)	d^{-1}	0.0191
Pore-size distribution index (n)	-	1.224
Tortuosity parameter in the conductivity function (l)	-	0.5

HYDRUS-1D model Setup

Boundary Conditions

- **Upper Boundary Condition:** Variable pressure head/flux
- **Lower Boundary Condition:** Free drainage



Input parameters

- **Top flux:** (**Irrigated water +Rainfall**)-**Evaporation***
- **Daily Potential Transpiration***
- **Root Distribution-** Assumed to be (90 cm)† and extends horizontally up to 2 m

*Calculated by Panmen Monteith Equation †Based on discussions with local farmers

HYDRUS-1D model Setup

Calculation of Irrigated water per day (Flood Irrigation)

Irrigated on 1 Acre of orchard (198 trees) for 12 h in a day:

$$1\ Acer = 4046.87\ m^2$$

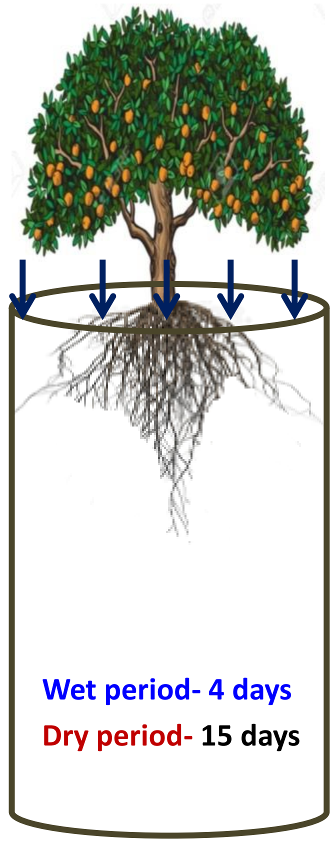
$$\boldsymbol{Discharge\ rate\ of\ Bore\ well} = 3.2\ \frac{l}{s}$$

$$3.2\ \frac{l}{s} \times 60 \times 60 = 11520\ \frac{l}{h}$$

Water is applied for 12 h in a day:

$$11520 \frac{l}{h} \times 12\ h = 138240 \frac{l}{d} = 138.24\ \frac{m^3}{d}$$

$$\textbf{Applied water on unit area} = \frac{138.24\ \frac{m^3}{d}}{4046.87\ m^2} = 0.034156\ \frac{m}{d} = \mathbf{3.42} \frac{\boldsymbol{cm}}{\boldsymbol{d}}$$



HYDRUS-1D model Setup

Scaling down sap flow data

- The **circumference (S_T)** of the orange tree was 0.52 m
- The **sapwood area (S_A)** was calculated as 0.30 m^2 (Granier A., 1987)

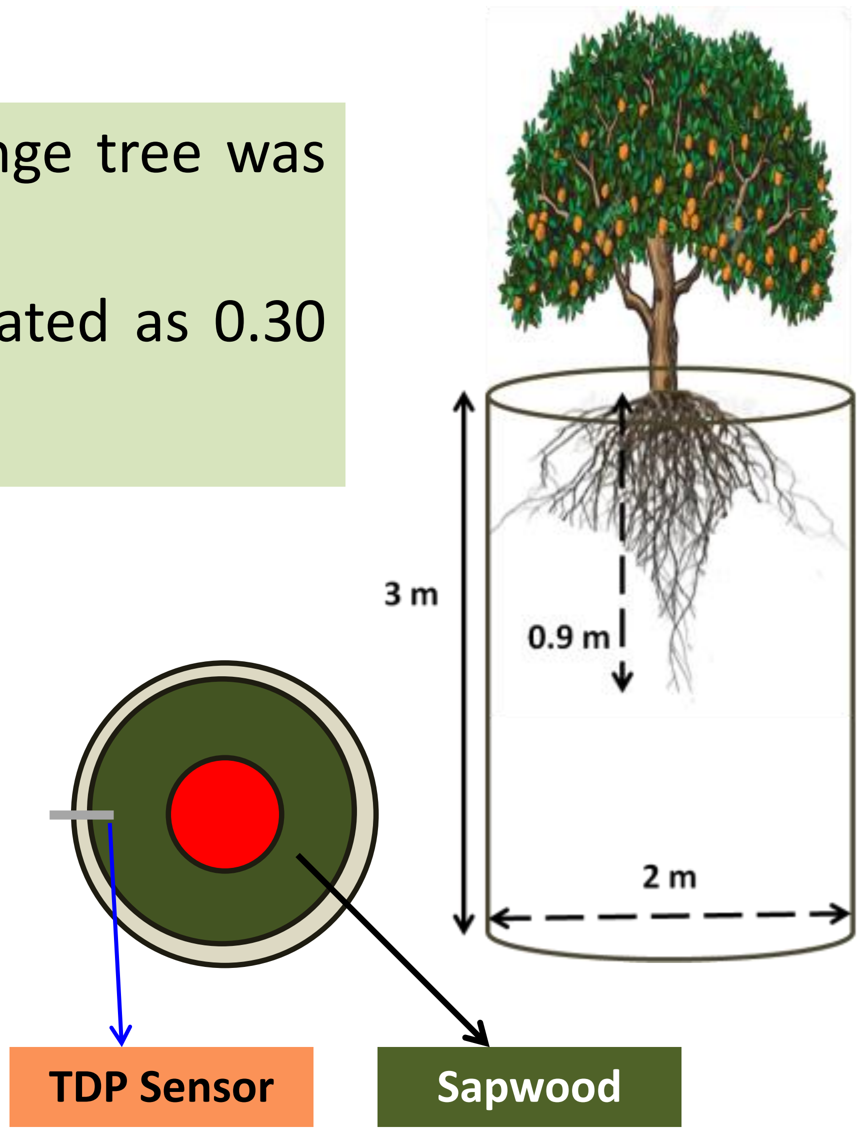
$$S_A = -0.0039 + 0.59\, S_T$$

Scaled Sap Velocity (V)

$$V = (S_A \times V_{sap})/\pi\, r^2$$

r = Radius of root spread

V_{sap} = Measured sap velocity



Experimental Set-up





Thermal Dissipation Probe (TDP) sensors
Make: Dynamax Inc., U.S.A.

CR1000X Measurement and Control Datalogger,
Make: Campbell Scientific, Inc., U.S.A

5 Year old orange tree (Young)
Tree Height: 2.7 m
Circumference: 25 cm

15 Year old orange tree (Mature)
Tree Height: 3.4 m
Circumference: 52 cm

SM150 Soil Moisture Probe,
Make: ΔT, U.K.

Automatic Weather Station
Make: Rainwise Inc. U.S.A.

Estimation of Potential Evapotranspiration Rate

Penman-Monteith equation

$$\mathbf{ET_o} = \frac{\mathbf{1}}{\boldsymbol{\lambda}}\left[\frac{\Delta(\mathbf{R_n} - \mathbf{G})}{\Delta + \boldsymbol{\gamma}\,(\mathbf{1} + \mathbf{r_c}/\mathbf{r_a})} + \frac{\boldsymbol{\rho}\mathbf{c_p}(\mathbf{e_a} - \mathbf{e_d})/\mathbf{r_a}}{\Delta + \boldsymbol{\gamma}\,(\mathbf{1} + \mathbf{r_c}/\mathbf{r_a})}\right]$$

ET_o = Potential evapotranspiration rate

λ = Latent heat of vaporization

Δ = Slope of the vapor pressure curve

R_n = Net radiation at surface

G = Soil heat flux

γ = Psychrometric constant

r_c = Crop canopy resistance

r_a = Aerodynamic resistance

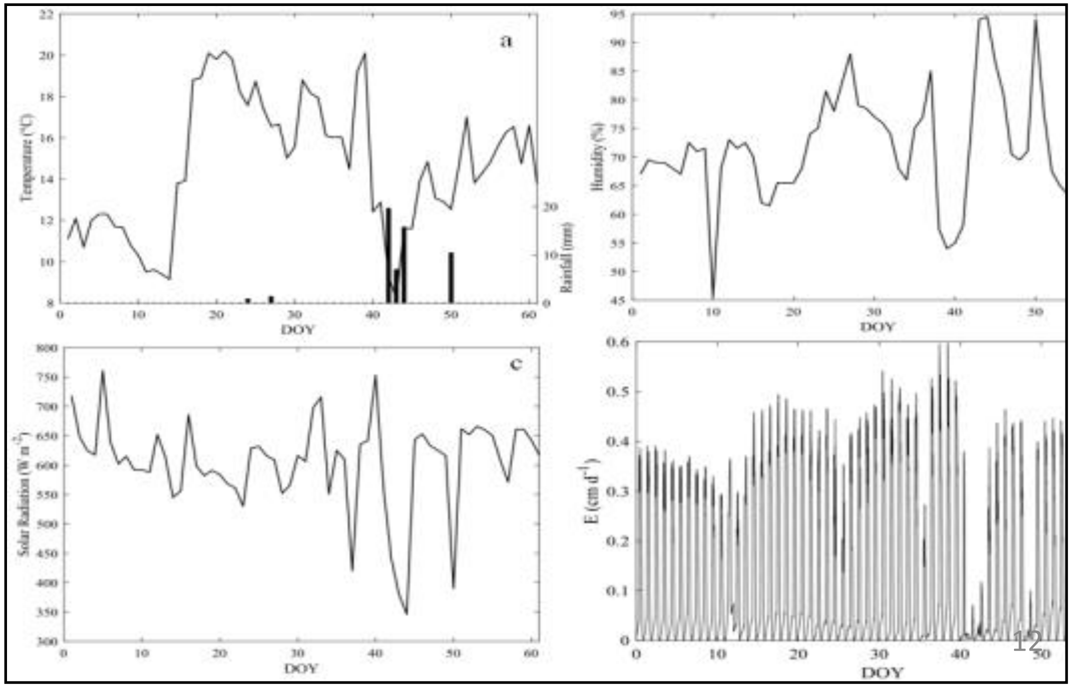
ρ = Atmospheric density

c_p = Specific heat of moist air

e_a = Saturation vapor pressure at T

e_d = Actual vapor pressure

Parameter	Source
Meteorological Parameters (Temperature, Relative Humidity, Wind Speed, Solar Radiation)	**Weather Station**
Soil Heat Flux	**NASA Satellite Data**
Cloud Fraction	
Net Heat Flux	



Partitioning and diurnal variation-PET

Partitioning of Potential Transpiration and Evaporation

$$T_p = ET_p\left(1 - e^{-k\,LAI}\right)$$

$$E_p = ET_p\, e^{-k\,LAI}$$

ET_p = Potential evapotranspiration, E_p = Pot. Evaporation, T_p = Pot. Transpiration

LAI = Leaf area index (4.2), k = Constant governing the radiation extinction by the canopy (0.5)

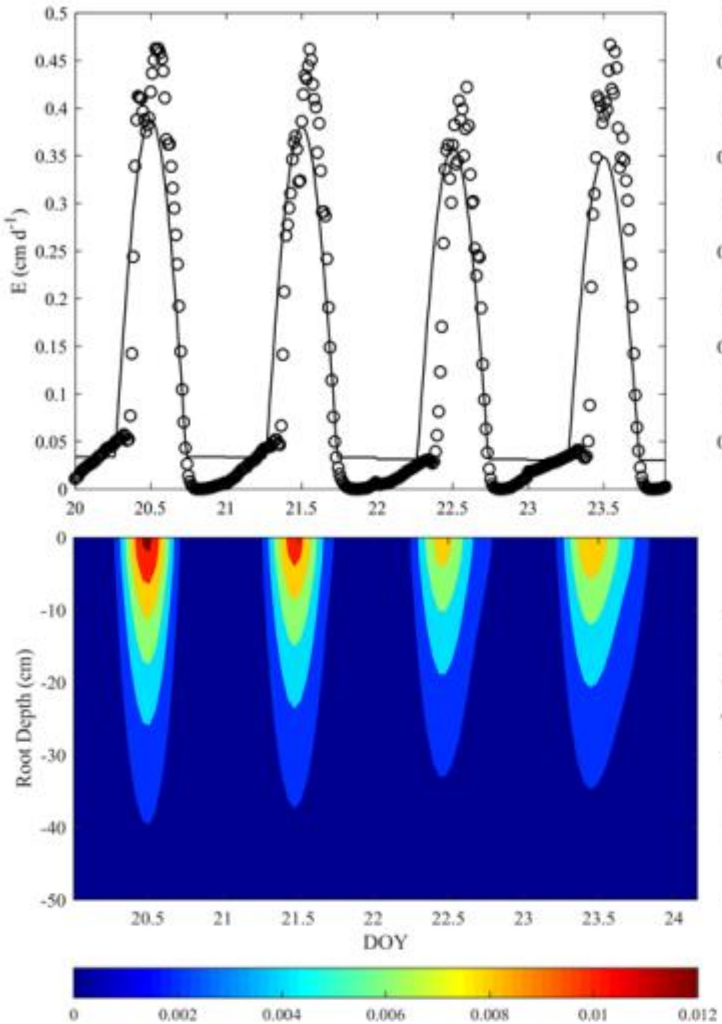
Diurnal Variation of Transpiration in HYDRUS-1D Model

$$T_p(t) = 0.24\overline{T_p} \qquad t < 0.264d,\ t > 0.736d$$

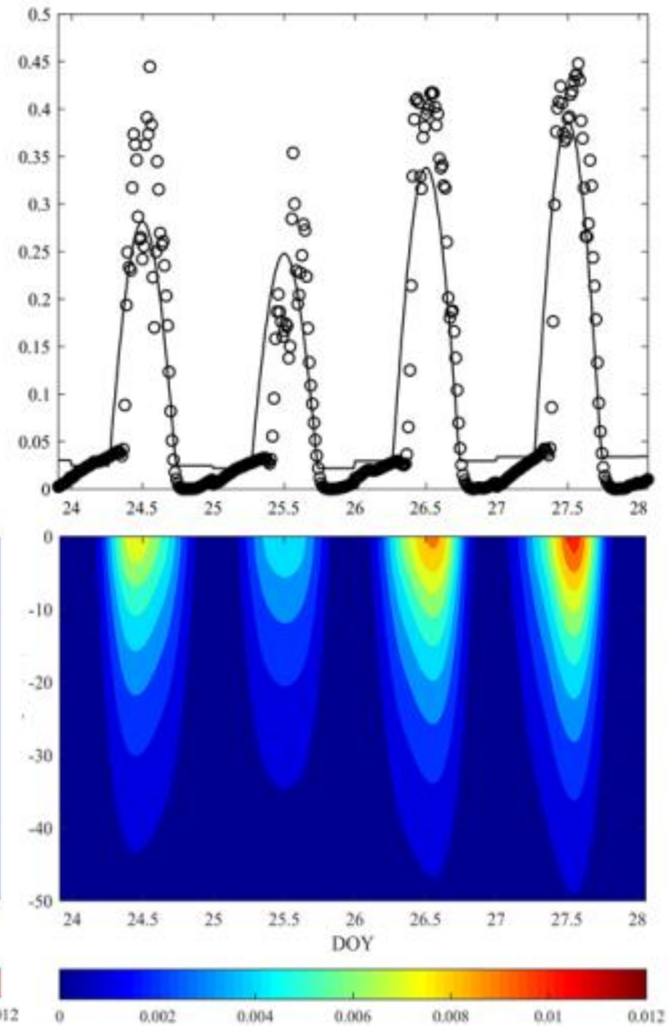
$$T_p(t) = \overline{T_p}\sin\left(\frac{2\pi t}{1\ day} - \frac{\pi}{2}\right) \qquad t \in (0.264d, 0.736d)$$

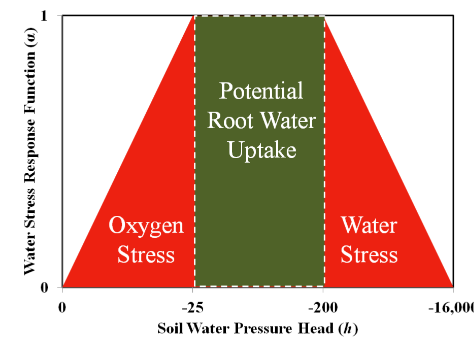
Validation of HYDRUS Model

WET Period (Irrigation)
December10-13, 2019



DRY Period (NO Irrigation)
(December 14-17, 2019)





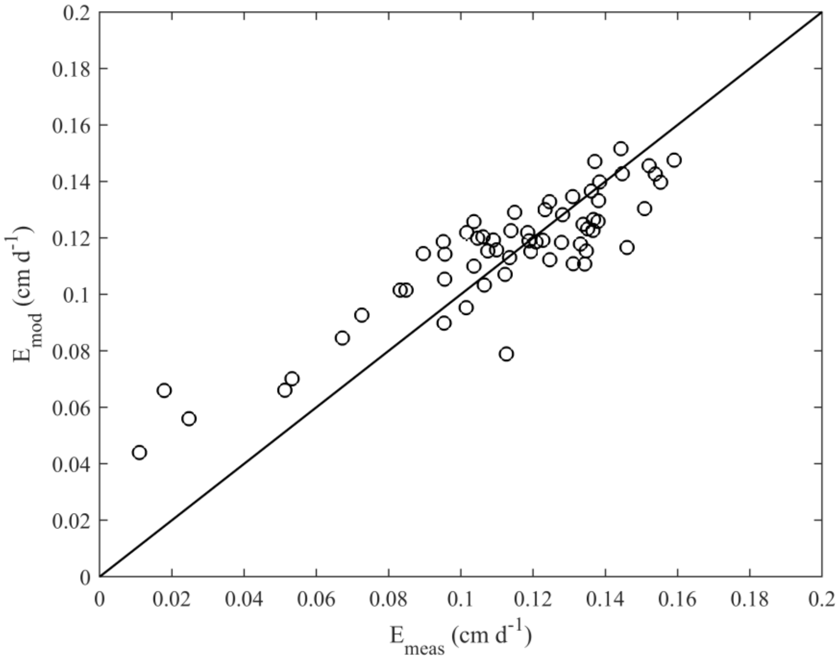
Orange tree are able to sustain relatively higher levels of oxygen stress

The root water uptake is higher during wet period compared to dry period

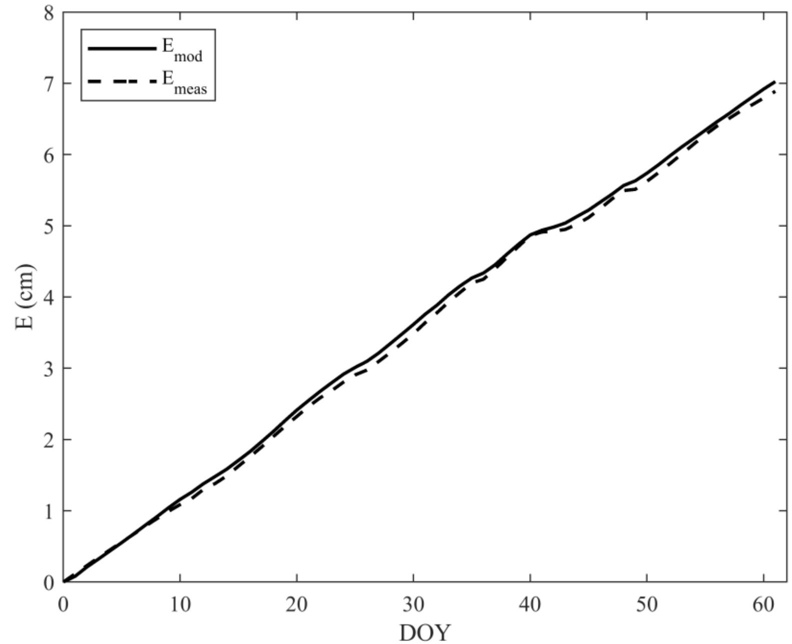
In dry period RWU is occurred from deeper root zone as compared to Wet period

Validation of HYDRUS Model

Modeled and Measured Transpiration



Observed Vs. Modeled Transpiration

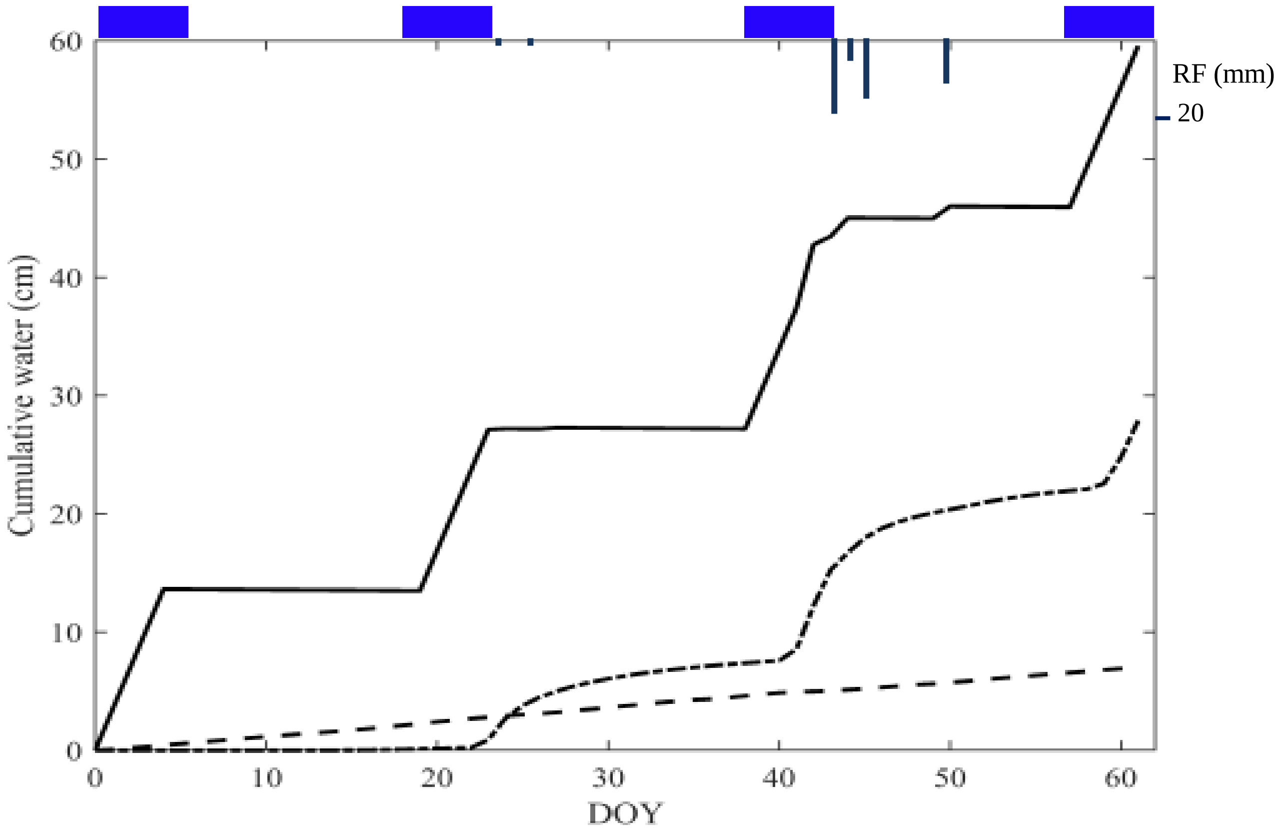


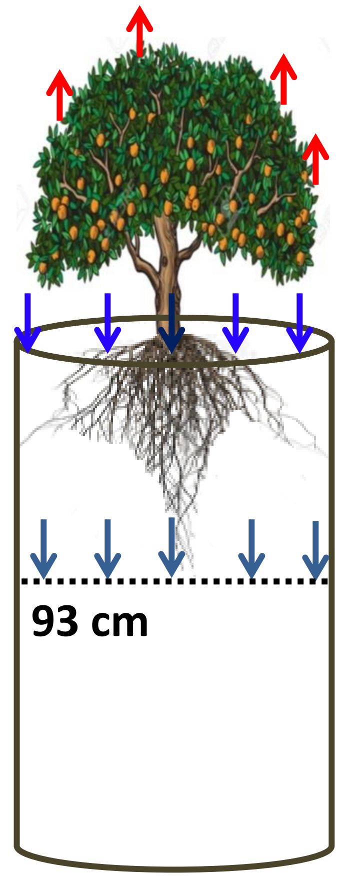
Cumulative Transpiration

Correlation Coefficient = 0.92
Nash–Sutcliffe efficiency (NSE)= 0.68

The model is able to reproduce sap flow values reasonably well

Results: Applied Flux, Transpiration and Drainage Below Root Zone

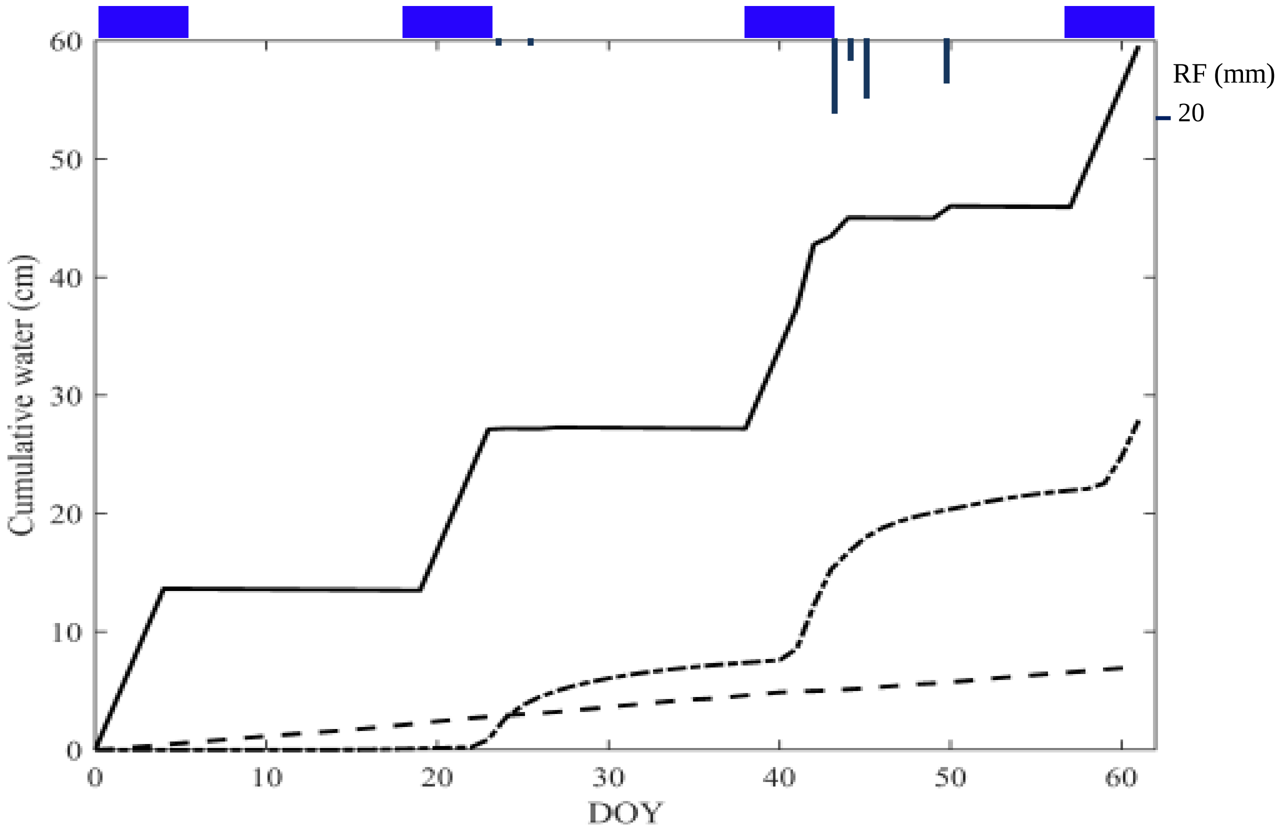


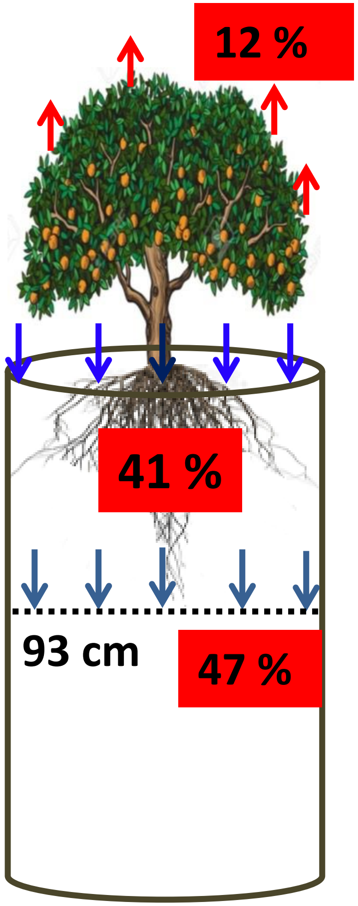


Drainage below the roots was 30.0 cm

Applied top flux is exorbitantly high

Results: Applied Flux, Transpiration and Drainage Below Root Zone





Drainage below the roots was 30.0 cm

Applied top flux is exorbitantly high and need to be optimised

Sensitivity Analysis

Sensitivity analysis is the study of the effect of the variation of input parameters on the output of the model

- Partial derivative based analysis
- Local or one-at-a-time (OAT) analysis

Global Sensitivity Analysis

Covers all the input parameters including the affect generated due to the interaction of the parameters

More accurate and can be applied on complex and non-linear models

Sensitivity Analysis

Variance based Sobol' method

- Variance based Sobol' method is a **widely used algorithm for environmental models**
- The variance of the model output can be decomposed in terms of different fractions
- Each fraction represents the affect of a particular parameter and its interaction with other parameters
- The sensitivity of parameters are expressed in terms of **sobol's sensitivity indices**

Sobol Total Sensitivity Index

$$S_{ti} = \frac{(1/2N)\sum_{j=1}^{N}\left[f(A)_j - f(A^iB)_j\right]^2}{(1/N)\sum_{j=1}^{N}\left[f(A)_j\right]^2 - f_o^{\,2}}$$

$$f_o = (1/N)\sum_{j=1}^{N} f(A)_j$$

Hartman et al., 2017

A and B are the two set of random input parameter matrices

A^iB represents a matrix where all the columns are from matrix A except ith column (from matrix B)

N=5000, Nossent et al (2011)

The total number of simulations

N (P+2) simulations =35000

Saltelli (2002)

Sensitivity Analysis

Steps of Sobol' Total Sensitivity Index Calculation

Select Input parameters and its minimum and maximum range

↓

Determine the total number of simulations for each matrix (N=5000)

↓

Generate Sobol quasi random numbers for matrix A & B using MATLAB

↓

linearly transformed parameters over the input space using range of each parameters

↓

Generate Matrix A1B, A2B, A3B, A4B, and A5B using matrix A & B

↓

Run HYDRUS 1D Model for all the combinations of Input Parameters (35000 Simulations)

Soil Hydraulic Parameters

Parameter	Lower limit	Upper limit
θ_r	0.055	0.1
θ_s	0.38	0.5
α	0.01	0.13
n	1.25	2.3
K_s	6.0	355.0

$$P_i = P_{min} + (random\ value \times (P_{max} - P_{min}))$$

A

θ_r	θ_s	α	n	K_s
a1	b1	c1	d1	e1
a2	b2	c2	d2	e2
a3	b3	c3	d3	e3
a4	b4	c4	d4	e4
.	.	.	.	.

B

θ_r	θ_s	α	n	K_s
a11	b11	c11	d11	e11
a22	b22	c22	d22	e22
a33	b33	c33	d33	e33
a44	b44	c44	d44	e44
.	.	.	.	.

A1B

θ_r	θ_s	α	n	K_s
a11	b1	c1	d1	e1
a22	b2	c2	d2	e2
a33	b3	c3	d3	e3
a44	b4	c4	d4	e4
.	.	.	.	.

A2B

θ_r	θ_s	α	n	K_s
a1	b11	c1	d1	e1
a2	b22	c2	d2	e2
a3	b33	c3	d3	e3
a4	b44	c4	d4	e4
.	.	.	.	.

A3B

θ_r	θ_s	α	n	K_s
a1	b1	c11	d1	e1
a2	b2	c22	d2	e2
a3	b3	c33	d3	e3
a4	b4	c44	d4	e4
.	.	.	.	.

A4B

θ_r	θ_s	α	n	K_s
a1	b1	c1	d11	e1
a2	b2	c2	d22	e2
a3	b3	c3	d33	e3
a4	b4	c4	d44	e4

A5B

θ_r	θ_s	α	n	K_s
a1	b1	c1	d1	e11
a2	b2	c2	d2	e22
a3	b3	c3	d3	e33
a4	b4	c4	d4	e44

Sensitivity Analysis

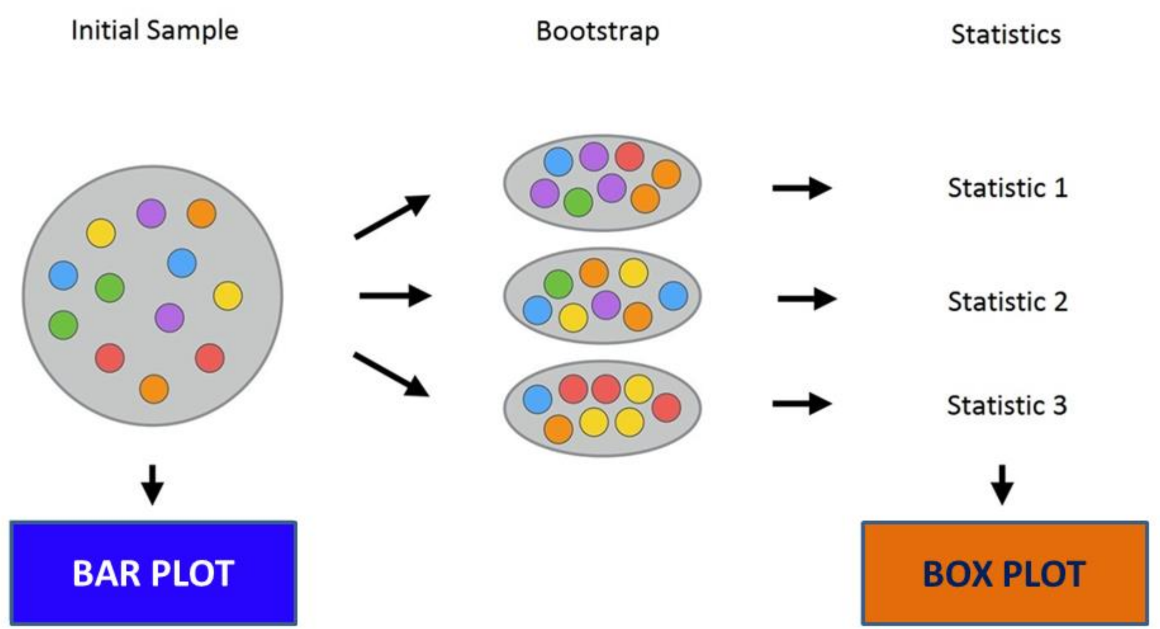
Bootstrap Confidence Interval (BCI)

Archer et al. (1997)

•To estimate the accuracy of the total sensitivity indices (variation)

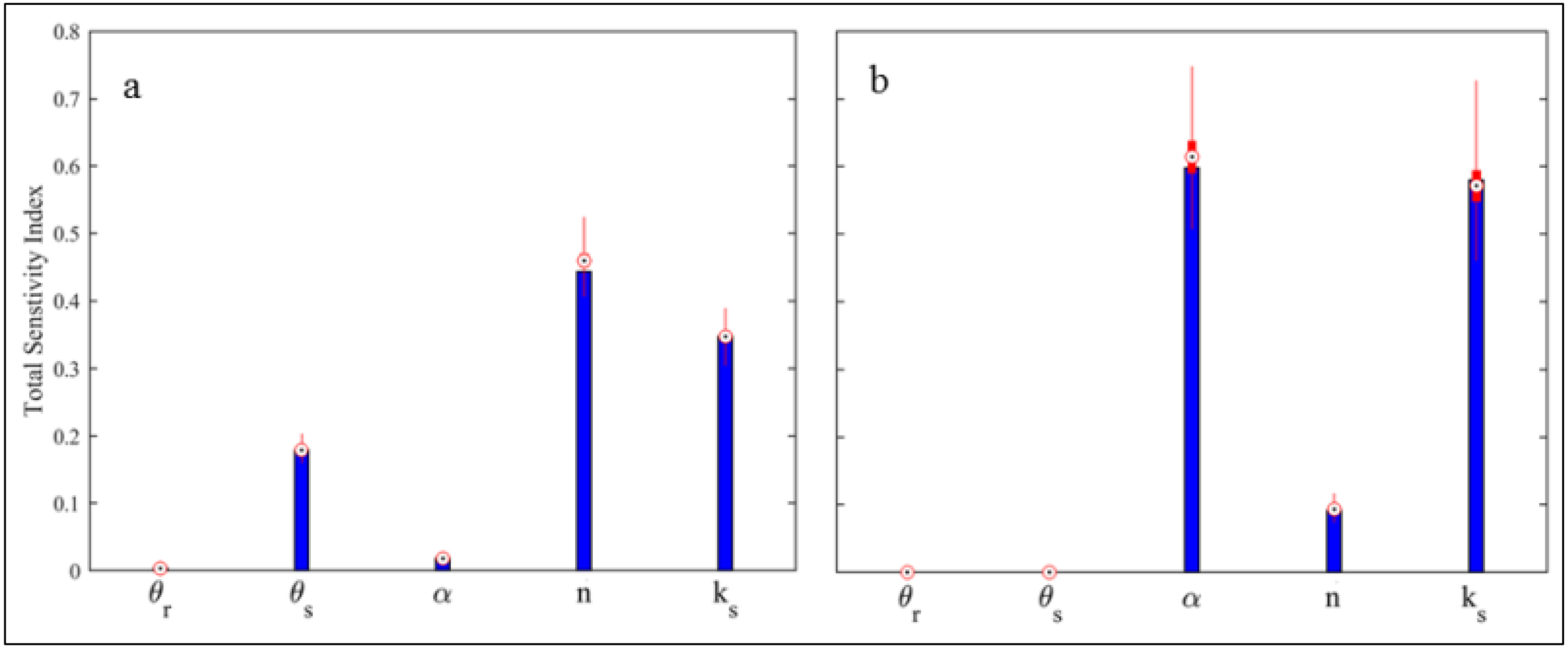
•Randomly re-sampling (2500 samples with replacement) from the output space of each matrix (5000)

•1000 values of total sensitivity indices calculated for each parameter



Sensitivity Analysis

Total Sensitivity Index



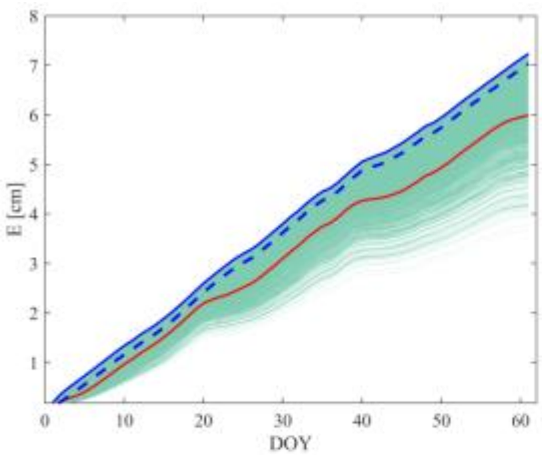
Drainage below root zone (-93 cm)

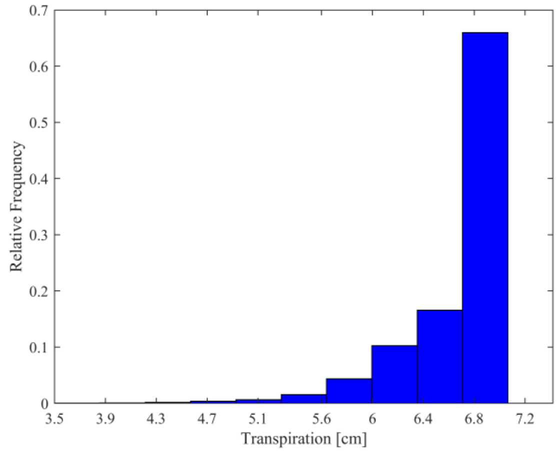
Transpiration

Parameter	Drainage below root zone		Transpiration	
	Total Sensitivity (%)	BCI	Total Sensitivity (%)	BCI
n	45	0.12	<10	0.043
K_s	36	0.085	58	0.27
α	<1	<0.001	60	0.24
θ_s	18	0.043	<1	<0.001
θ_r	<1	<0.001	<1	<0.001

Sensitivity Analysis

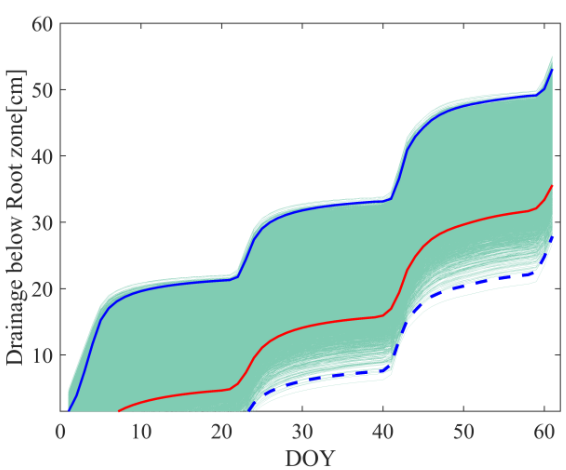
Transpiration

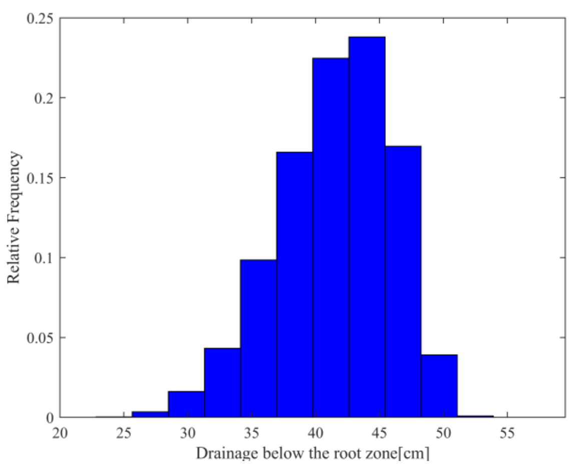




- The cumulative transpiration ranged between **3.5- 7.1 cm** (50% variation)
- In **clay type soil** the **oxygen stress** is developed due to low hydraulic conductivity
- In case of **sandy soil no water stress** developed and transpiration happens at potential rate (T_p) due to **high water application rate**
- Therefore the relative frequency distribution is **left skewed** and more than **60% simulations exhibit T_p**

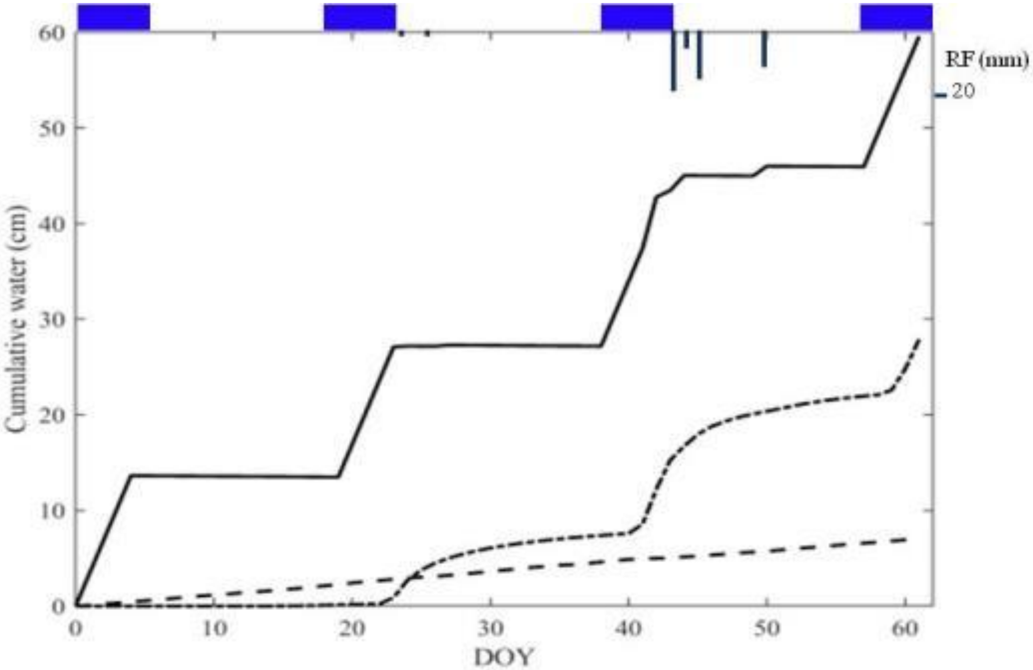
Drainage Below the Root Zone

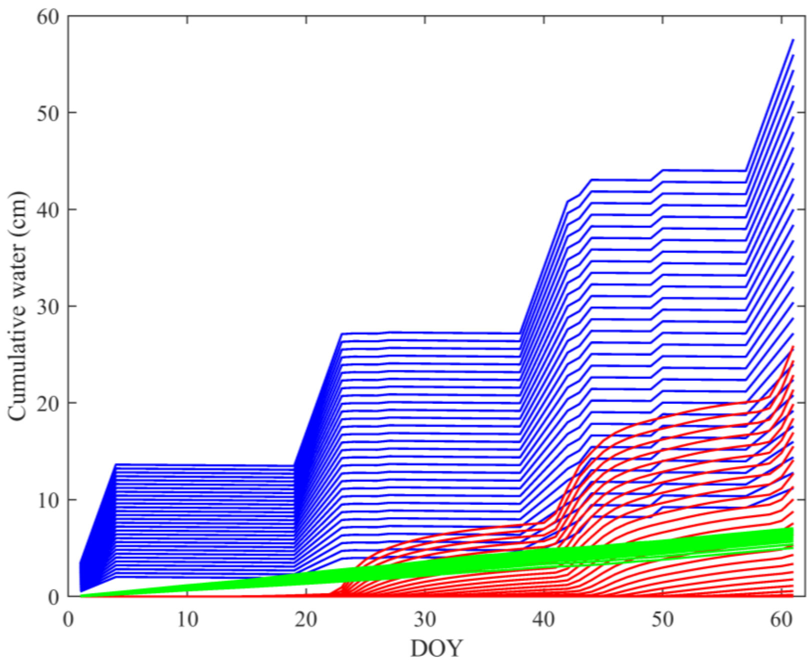




- The cumulative drainage below root zone ranged between **26-54 cm**
- **High drainage** observed towards **sandy soil**
- The relative frequency distribution is also **left skewed**

Irrigation Schedule Optimisation



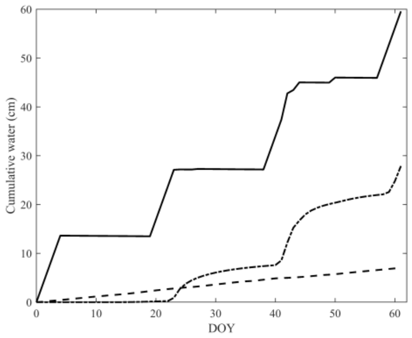


- ❑ **The water is getting stored in soil (23 cm)**
- ❑ Total 30 simulations -**Decreasing applied Top flux by 0.1 cm/day**
- ❑ **Lesser decrease in transpiration** than the drainage below root zone

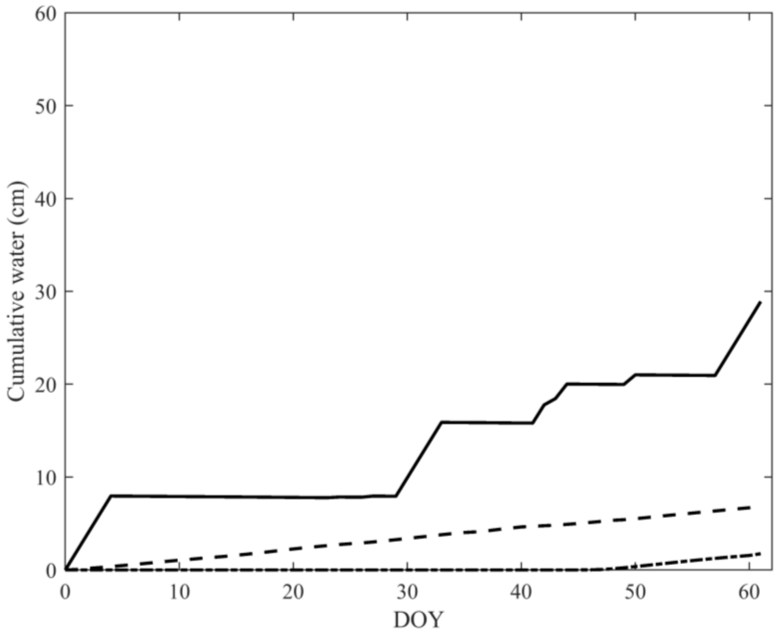
Irrigation Schedule Optimisation

Optimization Criteria

- ❑ Changing Applied Irrigation
- ❑ Changing Irrigation interval
- ❑ Changing Initial soil moisture condition

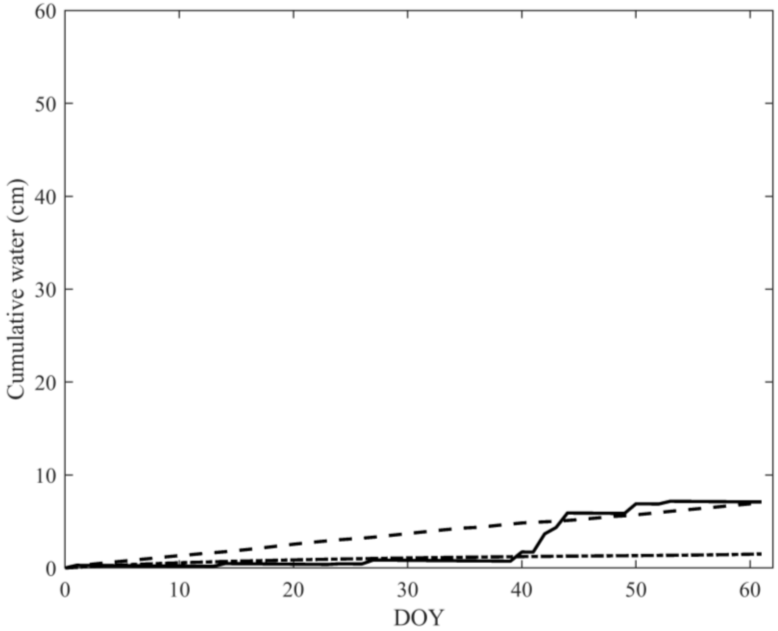


Initial soil moisture 0.2



2 cm per day for 4 days then 25 days interval

Initial soil moisture 0.33



0.3 cm per day at every 12 days interval

Conclusion

- **Good agreement** was achieved between HYDRUS-1D simulations and field measured sap flow
- The WUE for the present practice of flood irrigation was observed to be only 20%
- The GSA shows **pore-size distribution index** and **saturated hydraulic conductivity** has a major influence on the **leakage below the root zone**
- In contrast, the **air-entry-pressure parameter** and **saturated hydraulic conductivity** have a major influence on **transpiration**
- The initial conditions (Soil-water) play a significant role in calculating WUE
- Sensor based approach to trigger and control irrigation should be adopted for high WUE

THANK YOU

Does anyone have any question?

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