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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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 %)

<table>
<thead>
<tr>
<th>15-year old mature tree-Water usage, guidelines and practice (Liters/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Water Uptake (Sap flow method)</td>
</tr>
<tr>
<td>5.6</td>
</tr>
</tbody>
</table>

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:

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

The sink term can be defined as:

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

Relationship between $\theta$ and $h$, and $K$ and $\theta$

(van Genuchten-Mualem 1980):

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

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

$\theta = $ 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 $[LT^{-1}]$

$\theta_r = $ residual water content

$\theta_s = $ saturated water content

$\alpha = $ 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)
Feddes Curve for Orange Tree

Water Stress Response Function ($\omega$)

Soil Water Pressure Head ($h$)

Potential Root Water Uptake

Oxygen Stress

Water Stress

Feddes Curve for Orange Tree
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

<table>
<thead>
<tr>
<th>Soil Hydraulic Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated hydraulic conductivity ( (K_s) )</td>
<td>cm d(^{-1})</td>
<td>21.12</td>
</tr>
<tr>
<td>Saturated soil water content ( (\theta_s) )</td>
<td>-</td>
<td>0.4957</td>
</tr>
<tr>
<td>Residual soil water content ( (\theta_r) )</td>
<td>-</td>
<td>0.0992</td>
</tr>
<tr>
<td>The inverse of the air-entry value (or bubbling pressure) ( (\alpha) )</td>
<td>d(^{-1})</td>
<td>0.0191</td>
</tr>
<tr>
<td>Pore-size distribution index ( (n) )</td>
<td>-</td>
<td>1.224</td>
</tr>
<tr>
<td>Tortuosity parameter in the conductivity function ( (l) )</td>
<td>-</td>
<td>0.5</td>
</tr>
</tbody>
</table>
HYDRUS-1D model Setup

Boundary Conditions

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

Input parameters

• Top flux: \((\text{Irrigated water} + \text{Rainfall}) - \text{Evaporation}\) *
• 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:

\[ 1 \text{Acer} = 4046.87 \text{m}^2 \]

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:

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

Applied water on unit area \( = \frac{138.24 \frac{m^3}{d}}{4046.87 \text{ m}^2} = 0.034156 \frac{m}{d} = 3.42 \frac{cm}{d} \)
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 \( (V) \)

\[
V = \frac{(S_A \times V_{sap})}{\pi r^2}
\]

- \( r = \) 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

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

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

Automatic Weather Station
Make: Rainwise Inc. U.S.A.
Estimation of Potential Evapotranspiration Rate

**Penman-Monteith equation**

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

- \(ET_o\) = Potential evapotranspiration rate
- \(\lambda\) = Latent heat of vaporization
- \(\Delta\) = Slope of the vapor pressure curve
- \(R_n\) = Net radiation at surface
- \(G\) = Soil heat flux
- \(\gamma\) = Psychrometric constant
- \(r_c\) = Crop canopy resistance
- \(r_a\) = Aerodynamic resistance
- \(\rho\) = 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

\[
T_p = E T_p \left(1 - e^{-k \text{LAI}}\right)
\]

\[
E_p = E T_p \ e^{-k \text{LAI}}
\]

\(E T_p\) = 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

\[
T_p(t) = 0.24 \overline{T_p} \quad t < 0.264d, t > 0.736d
\]

\[
T_p(t) = \overline{T_p} \sin \left(\frac{2\pi t}{1 \text{ day}} - \frac{\pi}{2}\right) \quad t \in (0.264d, 0.736d)
\]
Validation of HYDRUS Model

**WET Period (Irrigation)**
December 10-13, 2019

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

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

Orange trees are able to sustain relatively higher levels of oxygen stress.

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

In the dry period, RWU is occurred from deeper root zone as compared to the 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
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 effect 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**

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

- 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 $i^{th}$ column (from matrix B).

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

Hartman et al., 2017

<table>
<thead>
<tr>
<th>N=5000, Nossent et al (2011)</th>
<th>The total number of simulations</th>
<th>N (P+2) simulations =35000</th>
</tr>
</thead>
</table>

Saltelli (2002)
**Steps of Sobol’ Total Sensitivity Index Calculation**

1. Select Input parameters and its minimum and maximum range
2. Determine the total number of simulations for each matrix (N=5000)
3. Generate Sobol quasi random numbers for matrix A & B using MATLAB
4. Linearly transformed parameters over the input space using range of each parameters
6. Run HYDRUS 1D Model for all the combinations of Input Parameters (35000 Simulations)

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**Soil Hydraulic Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_r$</td>
<td>0.055</td>
<td>0.1</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>0.38</td>
<td>0.5</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.01</td>
<td>0.13</td>
</tr>
<tr>
<td>n</td>
<td>1.25</td>
<td>2.3</td>
</tr>
<tr>
<td>$K_s$</td>
<td>6.0</td>
<td>355.0</td>
</tr>
</tbody>
</table>

\[ P_i = P_{min} + (\text{random value} \times (P_{max} - P_{min})) \]
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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Drainage below root zone</th>
<th>Transpiration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Sensitivity (%)</td>
<td>BCI</td>
</tr>
<tr>
<td>$n$</td>
<td>45</td>
<td>0.12</td>
</tr>
<tr>
<td>$K_s$</td>
<td>36</td>
<td>0.085</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>&lt;1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>18</td>
<td>0.043</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>&lt;1</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

- **Drainage below root zone (-93 cm)**
- **Transpiration**
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
- 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
• **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.
Does anyone have any question?

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