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System Dynamic Model Of 1-Dimensional Unsaturated Water And Solute Transport For Predicting Salinity Stress In Crops

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SYSTEM DYNAMIC MODEL OF 1-DIMENSIONAL UNSATURATED WATER AND

SOLUTE TRANSPORT FOR PREDICTING SALINITY STRESS IN CROPS

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Dedication

I would like to dedicate this thesis to my beloved wife and all my family members back home.

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by

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Abstract

There is a complex non-linear system dynamic between the water and salt transport in the unsaturated vadose zone where the salt transport and accumulation affect the water fluxes and vice versa. In addition, factors such as precipitation, transpiration, water infiltration and solute transport in the unsaturated zone of subsurface soil further complicate the processes involved. We have developed a system dynamics model for simulating the one-dimensional unsaturated water and solute transport along with root water uptake in the vadose zone. The model uses finite difference method for solving Richard's equation with a sink term for water transport and root water uptake; and advection-diffusion equation for solute transport. The stock–flows for water and solute transport is discretized into different soil layers from top until it leaches out into an end stock. The root water uptake, water and solute transport are interconnected using physically based formulations and empirical assumptions. The model predicts the impact on root water uptake due to water and salinity stress as a function of matric and osmotic potential. The model's results were similar to the results from HYDRUS showing that the model is capable of predicting salinity and matric stress in crops and could be a useful tool for analyzing various geographical soil and crops.

El Paso county is located in the Chihuahua desert in Texas in an arid region with prolonged drought conditions. In order to evaluate the salt accumulation in the soil layers, we revisited a severe drought period in the history of El Paso with record low rainfall from 1947 to 1956. The system dynamic model was used to simulate water infiltration, solute transport and root water uptake for cotton and pecan crops with five different combinations of irrigation water. These waters had a common source as rainfall and two other sources of river and groundwater bringing an influx of solute into the system. Irrigation water with 100% groundwater predicted the highest salt concentration in the root zone in the range of 10 mg/cm$_3$ (15.6 dS/m) whereas 100% river

water predicted the lowest in the range of 2 mg/cm_3 (3 dS/m). The assessment of root water uptake for the first and last ten years of simulation period showed a reduction in crop yield for pecan and cotton by 44% and 88%, respectively.

Table of Contents

List of Tables

List of Figures

Section 1 – Development and Simulation of Model and Comparison with Hydrus

1.0   Introduction

Irrigation in arid and semi-arid region is complicated due to the presence of salinity in soil. Salinity is caused due to the presence of high concentration of salts in the soil that reduces the amount of available water for root water uptake by plants. The reduction in the root water uptake combined with effects of drought and other environment conditions limits the productivity of crop plants by 20% -50% of their maximum yield (Shrivastava & Kumar, 2015). A wide range of salinity stress management strategies are required to overcome such impacts of salinity on crop productivity. Keeping track of salinity in the soil and its associated reduction in root water uptake/ transpiration and crop productivity is the first step in understanding the salinity stress. Modeling the soil water movement, root water uptake and solute transport plays an important role in assessing the salinity stress and its related impacts on crops (Šimůnek, Suarez, & Sejna, 1996). In addition, evaporation and plant transpiration also plays an important role in the solution composition, water and solute distribution in subsurface conditions (Šimůnek et al., 1996).

The first approach to understand the complex relationship of salinity and crop growth was quantified by physically measuring the salt tolerance of various crops in a laboratory condition (Bernstein, 1956). This was followed with separate models on root water extraction using microscopic (Gardner, 1960; Molz, Fungaroli, Drake, & Remson, 1968) and macroscopic approaches (Dutt, Shaffer, & Moore, 1972) and salt transport (Bresler, 1973). The first combined model for soil water flow and root water extraction was proposed by (Nimah & Hanks, 1973). A comprehensive model combining soil water flow in unsaturated soil, root water extraction and solute transport was developed by Childs (1975) as an extension to the work by Nimah & Hanks (1973).

Later, various numerical models for the simulation of 1-dimensional water flow and solute transport were developed. These models were broadly categorized as steady-state and transient models. The steady state model, WATSUIT (Rhoades & Merrill, 1976) divides the root zone to four different zones vertically and assumes the root water extraction to be in the ratios of 40/30/20/10. It has a function of precipitation/ dissolution based on the presence or absence of $CaCO_3$ as an option. Whereas, the transient model simulates the continually changing soil water, salt effects on evapotranspiration, osmotic and matric effects on root water extraction, multi component major ion chemistry and transport, precipitation/dissolution, cation exchange, carbon dioxide - heat production and transportation. Some of the major transient models are ENVIRO-GRO (Pang & Letey, 1998), SALTMED (Ragab, 2002), SWAP (van Dam, 2000), UNSATCHEM (Šimůnek et al., 1996; D. L. Suarez & Šimůnek, 1997) and HYDRUS (Šimůnek, J., Huang, & van Genuchten, 1998; Šimůnek, J., van Genuchten, & Šejna, 2005; Šimůnek, M. Šejna, Saito, Sakai, & Genuchten, 2013; Vogel, Huang, & Zhang, 1996). The functionality of these models differs in the root water extraction component where SALTMED and ENVIRO – GRO uses an additive function whereas SWAP, HYDRUS and UNSATCHEM uses a multiplicative function while considering the osmotic and matric stress. Additionally, UNSATCHEM calculates the osmotic coefficient using the Pitzer equations from the major ion chemistry and incorporates a hydraulic reduction function due to salinity-sodicity interactions that further reduces the soil water flow. A comprehensive comparison of the simulated results on the yield of forage corn of these models has been done by Oster, Letey, Vaughan, Wu, & Qadir (2012). These models are developed using FORTRAN language and require an expertise personnel to integrate and modify various components as per user requirement. Whereas, system dynamic models provide the option for

participatory involvement from various stakeholders due to the simple, graphical and visual interactive platform of these models allowing easy modification and integration.

1.1   *System Dynamic Approach*

System dynamics is a graphical approach that can represent the dynamics of soil water flow, root water extraction and solute transport by numerically solving the finite difference equations at pre-determined timesteps. The system dynamic approach has been used for various hydrological and watershed studies (Keshta, Elshorbagy, & Carey, 2009; Ouyang, Xu, Leininger, & Zhang, 2016). A recent study using the system dynamic approach successfully simulated infiltration of water in the unsaturated zone using Darcy's equation showing the effectiveness of this approach (Huang, Elshorbagy, Barbour, Zettl, & Si, 2011). In this approach, the dynamic relation of the input, and its downward or upward movement is simulated based on the system's framework represented by equations and the feedback mechanism that is either reinforcing (positive feedback loop) or counteracting (negative feedback loop) (Huang et al., 2011). No studies were found that used the system dynamic approach to simulate the transient combined soil water flow, root water extraction and solute transport.

2.0   Model Overview

The objective of this study is to develop a system dynamic model simulating the transient soil water flow, root water extraction and solute transport in the vadose zone and quantify the effects of root water uptake under salinity and matric stress, and compare the results with a similar numerical model, HYDRUS. System dynamic models being graphical are easier to understand and visualize, particularly for non-expert stakeholders (e.g., growers). They use feedback loops to represent the systems that are reinforcing (positive feedback loop represented by "+") or counteracting (negative feedback loop represented by "-") as shown in Figure 1.1.

3
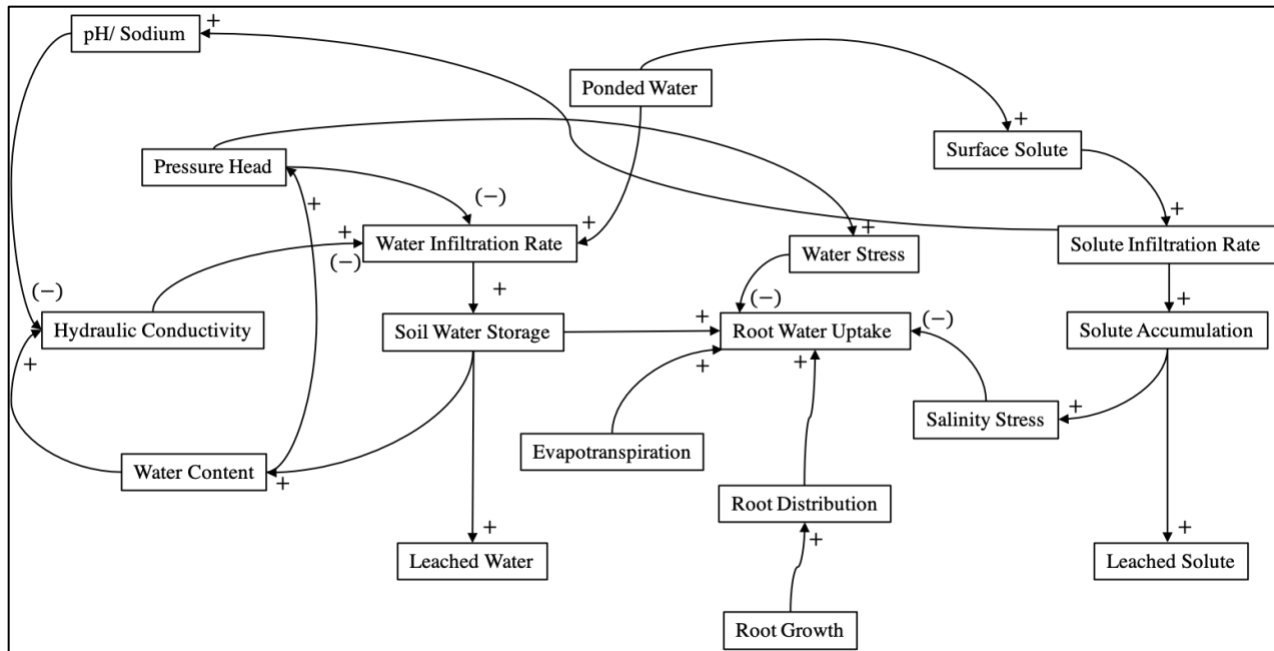
Figure 1. 1 – Casual loop diagram

During rainfall or irrigation event, the surface gets ponded with water. In due time, some water gets infiltrated and stored in the soil and; the rest leaches out. Once this system is in action, the loops formed by pressure head, hydraulic conductivity and water content becomes the driving force of the soil infiltration system. Increase in pressure head decreases the infiltration and increase in hydraulic conductivity increases infiltration, thus representing negative and positive feedback loops, respectively. When the roots of crop start to grow, it extracts water from the stored water in the soil. The extraction of water by roots increases the pressure head and in turn, builds up water stress on the crop reducing the crops ability to extract water from the soil layer, thus representing another negative feedback loop. Further, if the irrigation water or rain contains dissolved salt, it gets infiltrated into the soil and accumulates in the root zone. This accumulated salt will buildup salinity stress and sodacity of the soil. Salinity stress reduces the roots ability to extract water and; sodacity and pH reduces the hydraulic conductivity that in turn reduces the infiltration rate. This

is again represented by negative feedback loops. The system dynamic approach simulates these nonlinear, dynamic and complex relation between the systems using these feedback loops.

Further, system dynamic models have substantial educational and learning benefits for stakeholders compared to conventional numerical modeling. These models are easily editable by stakeholders to integrate any additional formulation or assumptions without prior knowledge of conventional programming languages. Also, there are methods to develop online web-based interface for system dynamic models and share them widely. Seeking participatory involvement from stakeholders was one of the key reasons for developing a system dynamic stock and flow-based model. Further other models such as HYDRUS does not simulate the effects of soil pH and clay swelling in soil water infiltration.

Soil is heterogenous in nature and a numerical solution of Richards equation is required for simulating the one-dimensional flow in unsaturated soil (Parissopoulos & Wheater, 1990). The system dynamic approach is used for numerically solving Richard's equation using finite difference method (Celia, Bouloutas, & Zarba, 1990). The unsaturated soil hydraulic properties are based on a set of closed-form equations (van Genuchten, 1980) and using the capillary model of Mualem (1976). Root water uptake is modeled using a sink term in Richard's equation that was first proposed by Feddes & Zaradny (1978) and later modified to include osmotic stress by van Genuchten (1987). Solute transport between multi soil layer is simulated by numerically solving the advection-diffusion equation for a non-reactive and non-interactive solute (Allan Freeze & Cherry, n.d.) using a finite difference method (Celia et al., 1990).

The model is developed using ISEE systems STELLA Architect software. A daily time step was used for all simulations. Due to the binary arithmetic that the computer uses, the time step between calculations, delta time (DT), in the model is set at 0.125 that falls in the sequence of

$(1/2)_n$, i.e., every $1/8_{th}$ of a day , thus optimizing the computational speed and avoiding round-off errors (ISEE Exchange).

Figure 1.2 shows the icon based skeletal structure of the model as depicted in the software interface. The model contains rectangular blocks that are the stock variables representing the accumulation of water and solute in soil layers, and water in roots. The soil water infiltration and root water uptake rate, and solute transport flux is simulated using the flow variable symbolized by valves, between the stocks. Variables and equation leading to the formulation of these flow variables are formulated using converters, symbolized by circles. The converters are connected to the flow variables using connectors symbolized by a line and arrow at the end.

The soil layer is divided into three compartments of 30 cm, 30 cm and 40 cm each measured from the top adding up to 100 cm of soil column under simulation that covers most of the root zone for irrigated cotton and pecan crops. The rainfall, irrigation water, evapotranspiration, root growth, consumptive water use of crops and salt concentration for a pre-defined time frame is loaded to a converter as a csv or excel file. By defining the root growth, consumptive water use, salt tolerance and root distribution, the model can be used to simulate various annual and perennial crops and presently, the model is simulated for cotton and pecan.

The model has four sectors namely, "Soil Water Flow" (SWF) simulating the unsaturated water flow, "Solute Transport" (ST) simulating the transport of solute between layers, "Root Water Uptake" (RWU) simulating extraction of water by roots under matric and osmotic stress from each layer and "Hydraulic Reduction" (HR) simulating the salt stress on soil water flow; as shown in Appendix A1, A2, A3 and A4. All of the four sectors are interconnected based on various formulations and empirical relations. STELLA gives a user the option for partial simulation by selecting one or more of the four sectors to be run individually and/or combined.
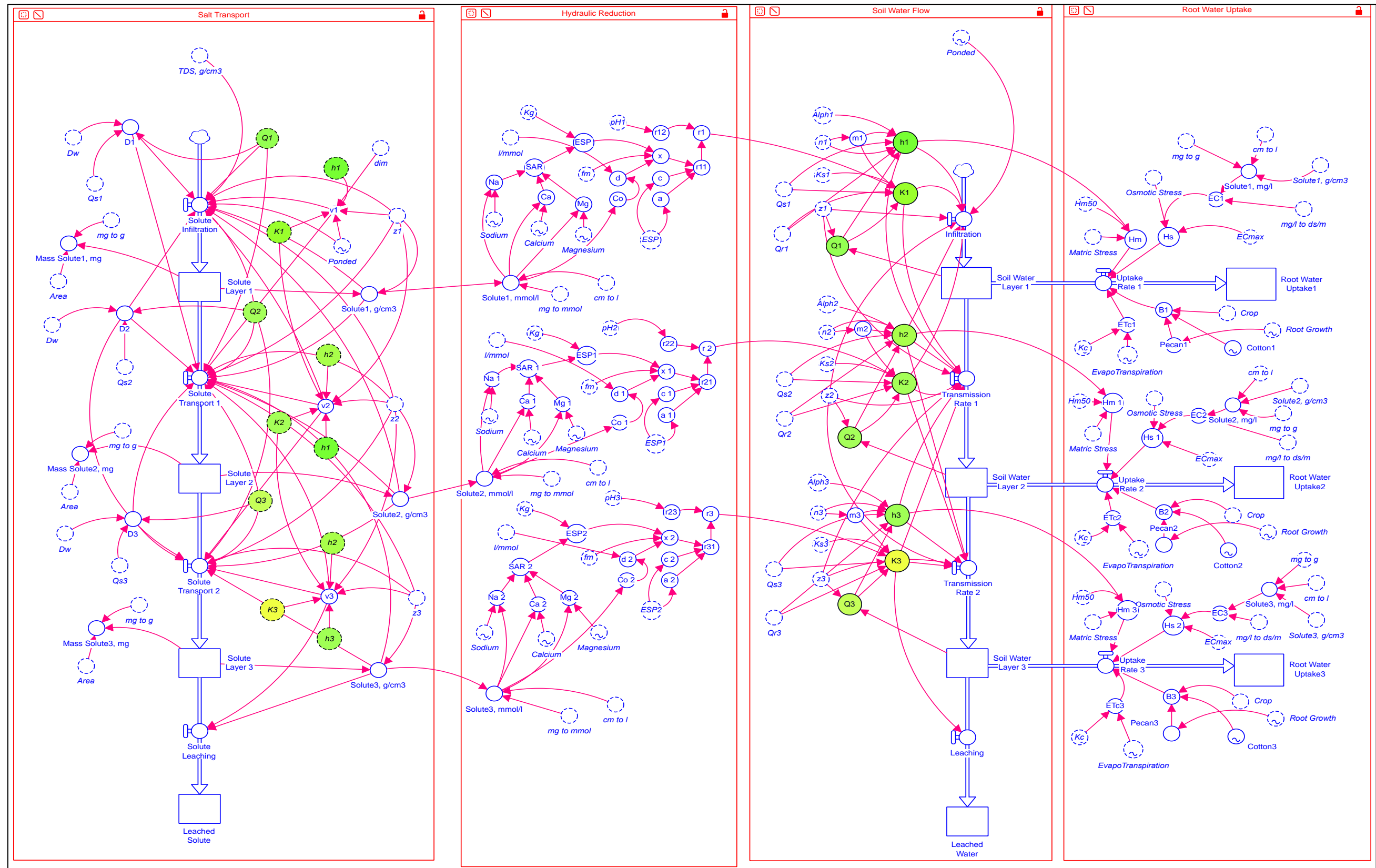
Figure 1. 2 – Icon based model skeletal structure as depicted in STELLA software

The building blocks within a selected sector is run dynamically keeping all other blocks static. This allows the user to set various combination of simulation based on the presence and absence of salt and matric stress.

The initial and top, and bottom boundary conditions for the SWF and ST sectors are assumed to be having a surface ponding due to rainfall and irrigation; and free drainage boundary conditions, respectively. The initial and top boundary condition is formulated using converters whereas the bottom boundary conditions is formulated using flow. The free drainage bottom boundary condition flows out to an end stock representing leached out solute and water from the soil.

3.0   Model Approach

The model is developed using the stock – flow – converter-based system dynamic approach to simulate the soil water movement, root water extraction and solute transport. The soil water flow in the unsaturated zone is considered as one-dimensional flow where the downward flow is driven by the hydraulic conductivity and pressure gradient of water. Coupled with the effects of solute buildup in the soil layer and root water extraction due to transpiration, the model simulates the water and solute movement and buildup in and below the root zone.

3.1   Soil Water Flow Sector (SWF)

The one-dimensional water flow in an unsaturated incompressible porous media is best described using the modified form of Richard's equation (Richards, 1952) formulated as:

$$\frac{\partial \theta}{\partial t} \; = \; \frac{\partial}{\partial z}\left[K\left(\frac{dh}{dz} + 1\right)\right] - S \qquad\qquad 1$$

where θ is the water content (cm^3 cm^{-3}), h is the water pressure head/ capillary suction (cm), t is time (days), z is the depth of soil layer (cm) and S is the sink term (cm^3 cm^{-3}day^{-1}) representing the root water extraction by the plants. The hydraulic conductivity and the capillary suction are

calculated using the Mualem (1976) and van Genuchten (1980) equations that was later modified to include the effects of soil chemical properties such as salt composition and *pH* (D. L. Suarez & Šimůnek, 1997):

$$\theta(h) \; = \; \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m}$$

2

and

$$rK(\theta) = \begin{cases} rK_s S_e^{1/2} \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 & S_e < 1 \\ rK_s & S_e \geq 1 \end{cases}$$

3

respectively, where

$$m = 1 - 1/n \qquad n > 1$$

4

$$S_e \; = \; \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

5

and where, θ_r and θ_s are the residual and saturated water content (cm3 cm-3), respectively; K_s is the saturated hydraulic conductivity (cm/ day); S_e is the relative hydraulic conductivity; r is the hydraulic reduction function due to the soil chemical properties; and n and α (cm-1) are the (van Genuchten, 1980) parameter of the soil water retention curve (SWRC).

3.1.1 Finite Difference Approximation

The conventional numerical solution of the Richard's equation considers the water balance of an infinitely small soil volume (Kroes, Van Dam, Groenendijk, Hendriks, & Jacobs, 2008) whereas in the system dynamic approach, the soil layer are considered as the stock variables and the rate of water movement is represented by the flow variables. Thus, an implicit backward finite difference method is used to solve the Richard's equation transforming it to a discretized form (Kroes et al., 2008):

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Delta z_i}\left[K_{i-\frac{1}{2}}\left(\frac{h_{i-1} + h_i}{\frac{\Delta z_{i-1} + \Delta z_i}{2}} + 1\right) - K_{i+\frac{1}{2}}\left(\frac{h_i + h_{i+1}}{\frac{\Delta z_i + \Delta z_{i+1}}{2}} + 1\right)\right] - S_i$$

6

where subscript i represents the ith soil layer with values ranging from 1 to 3 and Δz_i is the soil compartment thickness. The sink term, S_i representing root water extraction is calculated as a separate stock – flow variable from each soil layer. Before defining the equations for flow between the soil layers, the boundary conditions should be defined for accurate simulation.

3.1.1.1 Boundary Conditions

The initial and top boundary condition is the flux of water entering the soil due to rainfall and irrigation represented by the converter 'Ponded depth' (P) (cm/day) given by:

$$P = Rainfall\ (cm/day) + Irrigation\ Water\ (cm/day) \qquad 7$$

For the initial condition, the data for daily rainfall and irrigation cycle is loaded as a datasheet in csv or Excel file. The bottom boundary condition is assumed to be free drainage condition represented by the converter '*Leaching*' equal to the hydraulic conductivity of the bottom and third layer (K_3). The drained or percolated water is collected to an end stock variable 'Leached Water' for tracking the amount of water drained out of the soil.

3.1.1.2 Water Flow Equations

The stock variable 'Soil Water Layer' (SWL) represent the water stored in the soil layers and therefore, the flow equations are multiplied by the soil compartment thickness, Δz_i.

In a flux controlled top boundary condition, the flow equation from the surface layer to the stock variable '*SWL1*' representing the water storage in first layer of subsurface soil has the term $K_{i-\frac{1}{2}}\left(\frac{h_{i-1}+h_i}{\frac{\Delta z_{i-1}+\Delta z_i}{2}}+1\right)$ replaced by flux of water entering the soil, P. The flow variable 'Infiltration' (I) (cm/day) representing this flow is given by:

$$I\ =\ P-\left[\frac{K_1+K_2}{2}\left(\frac{h_1-h_2}{\frac{z_1+z_2}{2}}+1\right)\right] \qquad 8$$

10

The downward flow equation from the '*SWL1*' to '*SWL2*' is formulated using the flow

variable '*Transmission Rate 1*' (T_1) given by:

$$T_1 = \left[\frac{K_1 + K_2}{2}\left(\frac{h_1 - h_2}{\frac{z_1 + z_2}{2}} + 1\right)\right] - \left[\frac{K_2 + K_3}{2}\left(\frac{h_2 - h_3}{\frac{z_2 + z_3}{2}} + 1\right)\right] \qquad 9$$

In a free drainage bottom boundary condition, the downward flow equation from '*SWL2*'

to '*SWL3*' has the term $K_{i+\frac{1}{2}}\left(\frac{h_i + h_{i+1}}{\frac{\Delta z_i + \Delta z_{i+1}}{2}} + 1\right)$ replaced with the hydraulic conductivity of the third

layer (K_3) is given by:

$$T_2 = \left[\frac{K_2 + K_3}{2}\left(\frac{h_2 - h_3}{\frac{z_2 + z_3}{2}} + 1\right)\right] - K_3 \qquad 10$$

Major stock (S), converters (C) and flow (F) variables of SWF sector is listed in

Appendix A5.

3.2   Solute Transport Sector (ST)

The solute transport in the subsurface soil under transient water flow condition is given by

(Allan Freeze & Cherry, n.d.; van Dam, 2000):

$$\frac{\theta \partial c}{\partial t} = |q|\frac{\partial c}{\partial z} + \frac{\partial}{\partial z}\left[\theta D_{Diff}\frac{dc}{dz}\right] \qquad 11$$

where, c is the total solute concentration per unit volume of soil (g/cm3); q is Darcy's

volumetric flux (cm/day); and, D_{diff} is the diffusion constant (cm2/day) given by (Kroes et al.,

2008; Millington & Quirk, 1961):

$$D_{Diff} = D_w\frac{\theta^{\frac{7}{3}}}{\theta_s^2} \qquad 12$$

where, D_w is the solute diffusion coefficient in free water having a value of 2 cm2/day, and

q is given by Darcy's law:

11

$$q = -K\left(\frac{\partial h}{\partial z} + 1\right)$$ 13

3.2.1 Finite Difference Approximation

The advection – diffusion equation is numerically solved using an explicit central finite difference scheme given by (Kroes et al., 2008):

$$\frac{\partial c}{\partial t} = \frac{1}{\theta_i \Delta z_i}\left[q_{i-1/2}c_{i-1/2} - q_{i+1/2}c_{i+1/2}\right.$$

$$\left. + \left(\frac{\theta_{i-1/2}D_{i-1/2}(c_{i-1} - c_i)}{1/2(\Delta z_{i-1} + \Delta z_i)} - \frac{\theta_{i+1/2}D_{i+1/2}(c_i - c_{i+1})}{1/2(\Delta z_i + \Delta z_{i+1})}\right)\right]$$ 14

In the system dynamic model, the stock and flow variables for the ST sector represent the solute transport flux between the soil layers and therefore, the above equation is multiplied by the thickness of the soil compartment, Δz_i. In order to calculate the solute concentration, c in the above equation, the output from stock variable is again divided by the soil compartment thickness.

3.2.1.1 Boundary Conditions

For the initial condition, the total solute concentration (mg/l) from rainfall, river and ground water is loaded as csv or Excel file using the converter '*TDS, mg/l*' and later converted to units of g/cm3 into converter '*TDS, g/cm3*'.

The top boundary condition is the total solute flux entering the soil (c_{top}) affected by the ponding depth due to rainfall and irrigation water calculated by multiplying initial solute concertation with ponded depth:

$$c_{top} = 'TDS, g/cm3' * 'Ponded'$$ 15

As bottom boundary condition follows the same principle of free drainage boundary condition, the drainage solute flux represented by flow variable '*Solute Leaching*' is the product of solute concentration and Darcy's volumetric flux of the third and last soil layer given by:

$$'Solute\ Leaching' = c_3 q_3$$ 16

The leached solute is collected to an end stock variable '*Leached Solute*' for tracking the amount of solute leached out of the soil column.

3.2.1.2 Solute Flux Equations

For the initial solute infiltration flux from the topsoil to the stock variable '*Solute Layer 1*' (*SL1*) representing the solute flux in first layer of soil surface, the equation is modified to represent the flux boundary condition. Thus, the solute flux is represented using flow variable '*Solute Infiltration*' (I_s) (g cm-2 day-1) given by:

$$I_s = c_{top} - \frac{z_1}{\theta_1 z_1}\left[\left(\frac{q_1 + q_2}{2}\right)\left(\frac{c_1 + c_2}{2}\right) + \frac{\left(\frac{\theta_1 + \theta_2}{2}\right)\left(\frac{D_1 + D_2}{2}\right)(c_1 - c_2)}{\left(\frac{z_1 + z_2}{2}\right)}\right] \qquad 17$$

The solute flux from *SL1* to *SL2* represented by flow variable '*Solute Transport 1*' (T_{s1}) (g cm-2 day-1) is given by:

$$T_{s1} = \frac{z_2}{\theta_2 z_2}\left[\left(\frac{q_1 + q_2}{2}\right)\left(\frac{c_1 + c_2}{2}\right) - \left(\frac{q_2 + q_3}{2}\right)\left(\frac{c_2 + c_3}{2}\right) + \frac{\left(\frac{\theta_1 + \theta_2}{2}\right)\left(\frac{D_1 + D_2}{2}\right)(c_1 - c_2)}{\left(\frac{z_1 + z_2}{2}\right)}\right.$$
$$\left. - \frac{\left(\frac{\theta_2 + \theta_3}{2}\right)\left(\frac{D_2 + D_3}{2}\right)(c_2 - c_3)}{\left(\frac{z_2 + z_3}{2}\right)}\right] \qquad 18$$

For the solute flux from *SL2* to *SL3*, the free drainage bottom boundary condition is considered and therefore, the equation for the flow variable '*Solute Transport 2*' (T_{s2}) is given by:

$$T_{s2} = \frac{z_3}{\theta_3 z_3}\left[\left(\frac{q_2 + q_3}{2}\right)\left(\frac{c_2 + c_3}{2}\right) + \frac{\left(\frac{\theta_2 + \theta_3}{2}\right)\left(\frac{D_2 + D_3}{2}\right)(c_2 - c_3)}{\left(\frac{z_2 + z_3}{2}\right)}\right] - c_3 q_3 \qquad 19$$

The total solute concentration (g/cm3) of each soil layer is calculated by multiplying the stocks '*SL1*', '*SL2*' and '*SL3*' with corresponding layer's soil depths in the converter Solute*i*. Major stock (S), converters (C) and flow (F) variables of ST sector is listed in Appendix A5.

3.3   *Root Water Uptake (RWU)*

RWU is the amount of water extracted by the roots from the water stored in the soil layer given by the sink term, S, in Richard's equation (Šimůnek et al., 1996). The model simulates the sink term as water extracted by the flow variable '*uptake rate i*' (URi) from the stock variable '*SWLi*' for each soil layer in the SWF sector, where i represent the three layers of soil. S is depended on the soil water stress, osmotic stress, root characteristics and evapotranspiration (Skaggs, van Genuchten, Shouse, & Poss, 2006).

3.3.1   *Root Growth*

Pecan and cotton are two crops commonly grown in El Paso where pecan is a perennial crop and cotton is an annual crop. The model simulates RWU for these two crops where the root length, r (cm) is loaded as a csv file. The root length for pecan is assumed to be constant at 80 cm (Miyamoto, 1982) and cotton is assumed to be linear according to the locally observed root length for irrigated cotton at El Paso (G. K. Ganjegunte, Clark, Parajulee, Enciso, & Kumar, 2018) for a growing period of 180 days as shown in Table 1.1.

Table 1. 1 – Cotton Root Length (cm)

Length (cm)	Crop Period (days)
0 - 25	0 – 20
25 – 40	21 – 30
40 – 75	31 – 50
75	51 - 180

3.3.2   *Percentage Root Distribution (β)*

Root water uptake is depended upon the distribution of roots beneath the soil. These have been quantified using various root length density (RLD) and root area density function. The availability of data is important for improving the accuracy of the model's prediction.

RLD for cotton (Zhi et al., 2017) has been used to calculate the percentage root distribution in the soil to match the root growth of cotton in El Paso as shown in Figure 1.2.

In order to estimate the normalized root distribution of pecan, its root is considered to be fully grown at the time of simulation having a span of 300 cm on either side and a total root length of 80 cm (Woodroof & Woodroof, 1934) as shown in Figure 1.3.
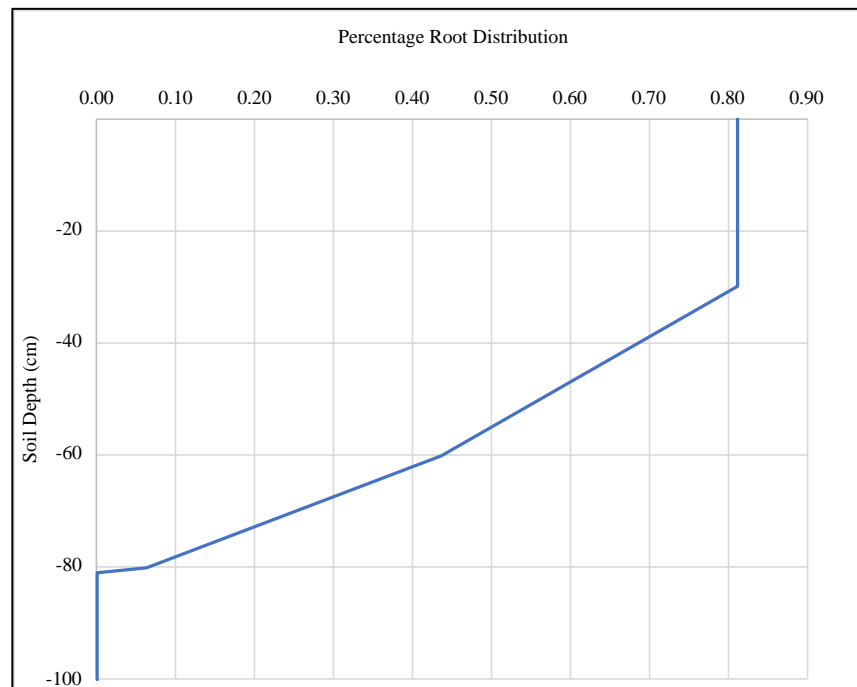
Figure 1. 3 – Root Length Density (cm/cm$_3$) for Pecan

For cotton, the varying root length density with depth is normalized over the root length as shown in Figure 1.4 (Zhi et al., 2017).
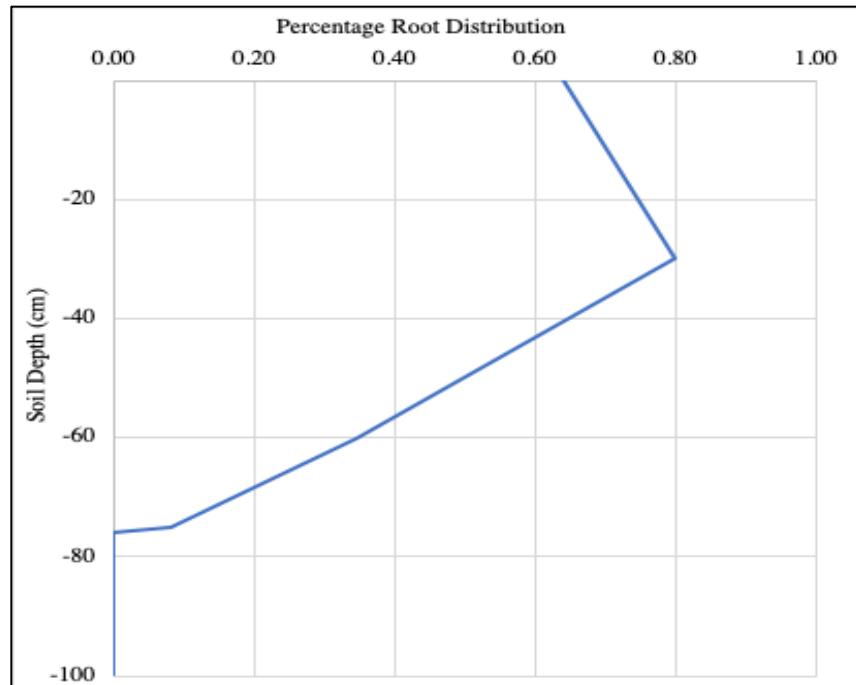
Figure 1. 4 – Percentage Root Distribution for Cotton

3.3.3 *Potential transpiration (Tp)*

For simplicity of calculation, the average potential evapotranspiration has been used for simulating root water uptake. Average potential evapotranspiration (ET_0) of El Paso for 52 years has been used for simulation purpose from Texas ET Network as shown in Table 1.2.

Table 1. 2 – Average ET_0 (cm/month)

Month	ET_0
January	7.0
February	9.0
March	15.4
April	20.8
May	25.0
June	28.2
July	23.3
August	22.7

Month	ET0
September	19.5
October	15.0
November	9.1
December	6.3

In order to predict the crop's consumptive or potential transpiration T_p (cm/day) use the crop's coefficient K_c for pecan has been adopted from (Miyamoto, 1982) and cotton from (Phocaides, 2000). represented by converter variable 'Etc' is calculated using equation:

$$T_p = K_c \, ET_0 \qquad\qquad 20$$

T_P is the potential transpiration at which the roots can extract water from the soil layer under most favorable conditions as shown in Figure 1.5 and 1.6.
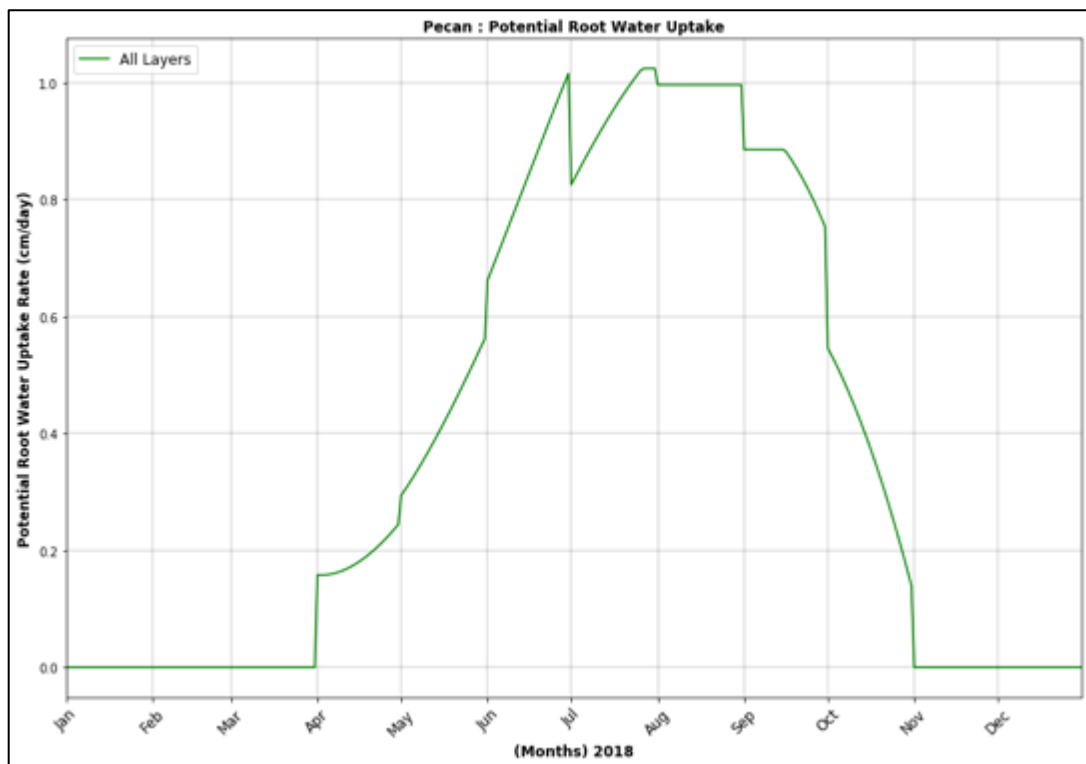
Figure 1.5 – Potential Water Uptake for Pecan (cm/day)
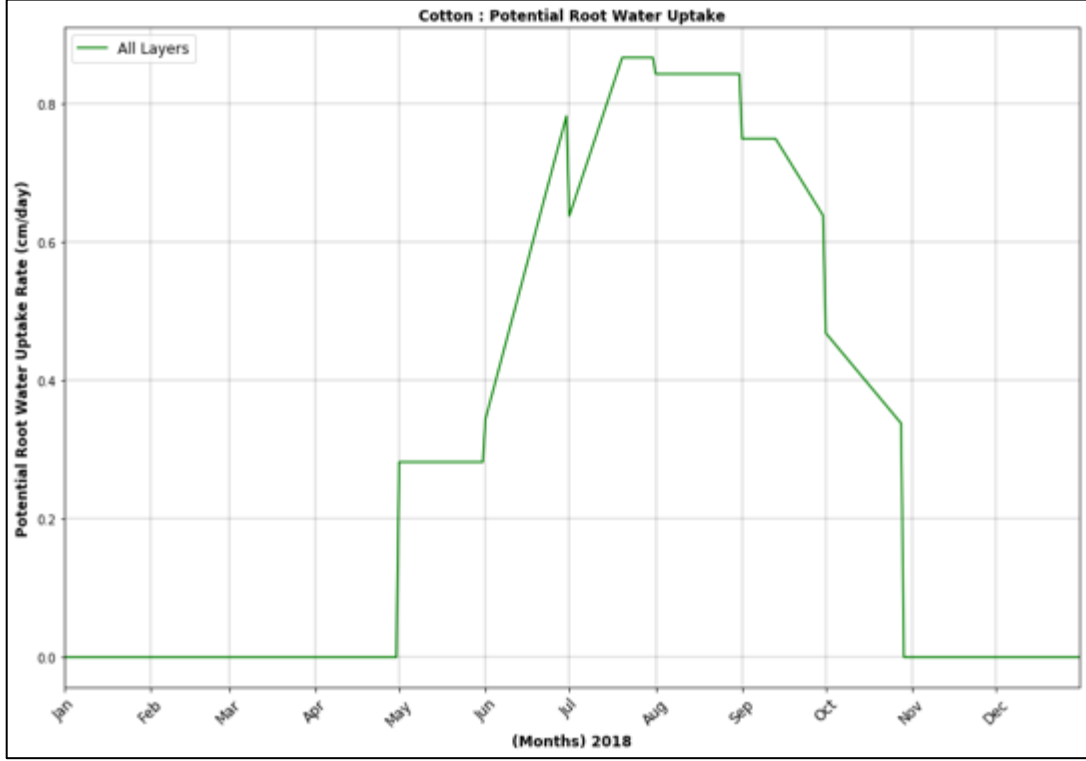
Figure 1. 6 – Potential Water Uptake for Cotton (cm/day)

3.3.4 Matric and Osmotic Stress

Matric stress is the reduction in RWU under water stress expressed as a water stress response function $(0 \leq \alpha(h) \leq 1)$ i.e., depended on the soil water pressure head, h calculated from converter variable 'hi' in SWF sector and empirical constant h_{50} representing the pressure head at 50% root water extraction having a value of -150 cm for pecan and -50 cm for cotton (Donald L Suarez, Vaughan, Brown, & Salinity, 2001; van Genuchten, 1987).

$$\alpha(h) \ = \ \frac{1}{1 \ + \ \left(\dfrac{h}{h_{50}}\right)^3} \qquad\qquad 21$$

Osmotic stress is the reduction on RWU under salinity stress due to the presence of salt in the soil water. It is expressed as an osmotic stress response function $(0 \leq \alpha(s) \leq 1)$ i.e., depended on the total salt concentration EC (dS/m) calculated from converter '$Solutei$' in ST sector and threshold value of crop salt tolerance, EC_{50} (dS/m) (Oster et al., 2012; van Genuchten, 1980).

$$\alpha(s) \ = \ \frac{1}{1 \ + \ \left(\frac{EC}{EC_{50}}\right)^3} \qquad\qquad 22$$

In order to calculate EC of soil water solution, unit of '*Solute$i$*' is converted to mg/l and then, empirically converted to dS/m using (Wallender & Tanji, 2011):

$$640 \cdot EC \ (ds/m) \ = \ TDS \ (mg/l) \qquad\qquad 23$$

where, *TDS* is the total salt concentration in soil water.

3.3.5   Uptake Equation

A macroscopic approach was adopted in calculating the sink term given by (Feddes, Kowalik, & Zaradny, 1978; van Genuchten, 1987):

$$S \ = \ \beta \ \alpha(h) \ \alpha(s)T_p \qquad\qquad 24$$

RWU from each soil layer is formulated using the flow variable '*Uptake Rate$i$*' (URi) connected to the stock variable '*SWLi*' and an end stock variable '*Root Water Uptake i*' inferring that the extracted water from soil layer is stored in the roots at a rate equal to the actual transpiration rate. Thus, the equation for flow variable *URi* is given by:

$$UR_i \ = \ \beta_i \ \alpha(h)_i \ \alpha(s)_i T_p \qquad\qquad 25$$

where, *i* represent the *ith* soil layer with *i* equal to 1,2 and 3. Major stock (S), converters (C) and flow (F) variables in RWU sector is listed in Appendix A5.

3.4   Hydraulic Reduction (HR) Function

The hydraulic reduction function, $(0 \leq r \leq 1)$, decreases the hydraulic conductivity due to the presence of exchangeable sodium and adverse pH in the soil. High level of exchangeable sodium causes clay dispersion and swelling of the soil (McNeal, 1968; Šimůnek et al., 1996; D. L. Suarez & Šimůnek, 1997). The pH effects the saturated as well the effective hydraulic conductivity (D. L. Suarez, Rhoades, Lavado, & Grieve, 1984). HR having a value of one represent that flow

is under no stress and less than one and greater than zero represent a flow with reduced hydraulic conductivity due to salt stress. The hydraulic reduction function is given by:

$$r = r_1 r_2 \qquad\qquad 26$$

where, r_1 is the effects of exchangeable sodium (McNeal, 1968; Šimůnek et al., 1996; D. L. Suarez & Šimůnek, 1997) and r_2 is the effects of adverse pH on the hydraulic conductivity (D. L. Suarez et al., 1984; D. L. Suarez & Šimůnek, 1997), respectively, given by:

$$r_1 = 1 - \frac{cx^n}{1 + cx^n} \qquad\qquad 27$$

where c and n are empirical parameters and x is the swelling factor given by:

$$x = 3.6 \times 10^{-4} f_{mont} \; ESP \; d \qquad\qquad 28$$

and

$$d = \begin{cases} 0 & for \; C_0 > 300 \; mmol \; l^{-1} \\ 356.4 \; C_0^{-1/2} + 1.2 & for \; C_0 < 300 \; mmol \; l^{-1} \end{cases} \qquad 29$$

and

$$n = \begin{cases} 1 & for \; ESP < 25 \\ 2 & for \; 25 \leq ESP \leq 50 \\ 3 & for \; ESP > 50 \end{cases} \qquad 30$$

and

$$c = \begin{cases} 35 & for \; ESP < 25 \\ 932 & for \; 25 \leq ESP \leq 50 \\ 25000 & for \; ESP > 50 \end{cases} \qquad 31$$

respectively,

where, f_{mont} is the weight fraction of montmorillonite in the soil assumed to be 0.1 (McNeal, 1968; Šimůnek et al., 1996); d is the adjusted interlayer spacing; C_0 is total salt concentration of the solution (mmol l-1) calculated from '*Solutei*' in the ST sector; and ESP is the exchangeable sodium percentage calculated from the sodium absorption ratio (*SAR*) given by (Wallender & Tanji, 2011) :

$$SAR = \frac{[Na]}{[Ca + Mg]^{1/2}} \qquad\qquad 32$$

Since the model does not simulate ion association or speciation, the total analytical concentrations (mmol l-1) of Sodium [Na], Calcium [Ca] and Magnesium [Mg] are calculated by assuming it to be present in the solution as a certain percentage of the total salt concentration. The percentage value is loaded as a csv file into the converter variable '*Sodium*', '*Calcium*' and '*Magnesium*'. For SAR calculation, unit of '*Solutei*' is empirically converted to mmol/l using (Tanji et al., n.d.):

$$Solute\ (mg/l) = Solute\ (mmol/l) \cdot 64 \qquad\qquad 33$$

and,

$$\frac{[ESP]}{[100 + ESP]} = k'_g SAR \qquad\qquad 34$$

where, k'_g is the modified Gapon selectivity coefficient having a value of 0.015 (mmol l)-1/2 (Wallender & Tanji, 2011). However, k'_g should be estimated based on site specific data (Doering & Willis, 1980; Jurinak, Amrhein, & Wagenet, 1984; Wallender & Tanji, 2011). The reduction factor, r_2, is calculated using the equation by D. L. Suarez et al., 1984:

$$r_2 = \begin{cases} 1 & pH < 6.83 \\ 3.46 - 0.36pH & 6.83 \le pH \le 9.3 \\ 3 & pH > 9.3 \end{cases} \qquad\qquad 35$$

Major stock (S), converters (C) and flow (F) variables in HR sector is listed in Appendix A5.

4.0 Model Parameters

4.1 Soil Hydraulic Properties

In order to obtain a realistic simulation of the dynamic process of soil solutions, the model require site specific hydraulic properties of soil. The soil properties of a commercially managed field

(31°30'32.30" N, 106°13'25.49" W) in El Paso County, Texas having an area of approximately 16 Ha was obtained from Web Soil Survey. The soil consists of Tigua (Tg - 72%), Glendale (Gs - 12%) and Harkey (Hs - 16%) silty clay loam as shown in Figure 1.7. The residual water content (θ_r) is an assumed value that can be optimized for running the model. The initial value of the stock variable "Soil Layer" is set as the maximum water holding capacity. A weighted average of the soil properties has been taken at each depth of soil as shown in Table 1.3. The air entry pressure, α (cm-1) and pore size distribution, n of the SWRC was not readily available and therefore a value of 0.0178 cm-1 for α and 1.30 for n has been assumed for all depths (Schaap & Van Genuchten, 2006).

Figure 1. 7 – Soil Map at (31°30'32.30" N, 106°13'25.49" W) in El Paso County, Texas

Table 1. 3 – Soil Hydraulic Properties

Soil depth (from Topsoil) (z) cm	Residual Water Content (θ_r) cm3 cm-3	Saturated Water Content (θ_s) cm3cm-3	Saturated Hydraulic Conductivity (K_{sat}) cm day-1	Soil pH	Maximum Water Holding Capacity (cm) ($z \times \theta_s$)
30	0.00	0.34	6.11	8.15	10.2
30	0.01	0.39	15.80	8.15	11.7
40	0.02	0.39	40.44	8.15	15.6

4.2   Rainfall and Irrigation Water

Daily rainfall for El Paso region was downloaded from Climate Data Online (CDO), National Climatic Data Center (NCDC) for the respective simulation time period. The irrigation cycle for pecan and cotton was set based on observed practice in El Paso region given in Table 1.4.

Table 1. 4 – Irrigation Cycle

Month	Day	Irrigation Water (cm)
Pecan		
May	01	12.7
	16	12.7
June	01	12.7
	16	12.7
July	01	12.7
	16	12.7
August	01	12.7
	16	12.7
September	01	12.7

Month	Day	Irrigation Water (cm)
	16	12.7
October	01	12.7
	16	12.7
	Total	**152.4**
Cotton		
May	01	12.7
June	30	12.7
July	15	12.7
August	04	12.7
	19	12.7
September	01	12.7
	Total	**76.2**

4.3   *Initial Salt Concentration (S_i)*

The ST sector in the model simulates the transport of salt entering the soil surface dissolved in rain (R), river (RW) and ground water (GW). The irrigated water is categorized as RW and GW based on their percentage contribution to the total amount of water.   Due to the absence of extensive monitoring salt data in the region, a constant amount of salt is considered to be dissolved in waters during the entire simulation period given in Table 1.5.

Table 1. 5 – Initial Salt Concentration (mg/l)

Salt Type	Total Dissolved Salts	Sodium	Calcium	Magnesium
Rainwater (S_R)	32	10.95	19.2	1.77
River Water (S_{RW})	512	106.94	101.38	16.52
Ground Water (S_{GW})	4627.2	1941	252	59.52

The above concentrations are observed chemistry of different water sources at a given time period in the El Paso region. The total amount entering the soil surface every day is based on the type of water used and daily ponding of the soil layer given by:

$$S_i = \frac{R \cdot S_R + RW \cdot S_{RW} + GW \cdot S_{GW}}{R + RW + GW}$$

(36)

5.0 Results and Discussions

The model simulates the dynamic process of transient water flow in subsurface soil and water extraction beneath the root zone under salinity and water stress. The accuracy of simulation and subsequent prediction of results are depended on the value of parameters closer to a site-specific data. Due to the non-availability of experimented site data, the soil hydraulic properties θ_s, θ_r, α, n and K_s has been calculated from the Web Soil Survey for a managed field at Texas A&M Agrilife in El Paso county, Texas. The salt concentration of irrigation water has been calculated from an initial value obtained from Texas A&M Agrilife and later generated for a desired time duration for different combination of rain, river water and groundwater. Root growth, consumptive use and root distribution has been assumed based on available site data and various literatures.

5.1 Simulation Setup

The simulation duration was set for 365 days representing year 2018. The crop is assumed to be irrigated using a supply of 30% groundwater and 70% river along with incident rainfall. As a result, the initial surface solute concentration (mg/cm3) is calculated using the salt concentration of rainfall, river water and groundwater in their appropriate ratios whereas the surface solute flux (mg cm-2 day-1) is calculated by multiplying the rainfall for year 2018 with surface solute concentration as shown in Figure 1.8, 1.9 and 1.10.
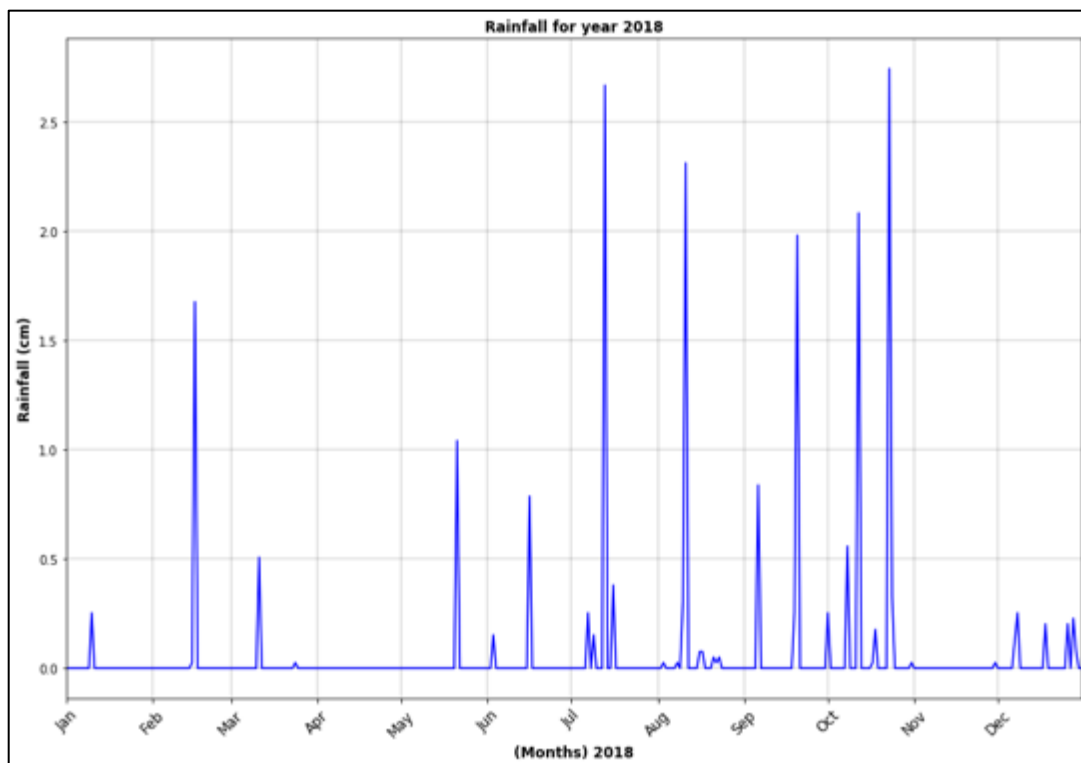
Figure 1. 8 – Rainfall for year 2018
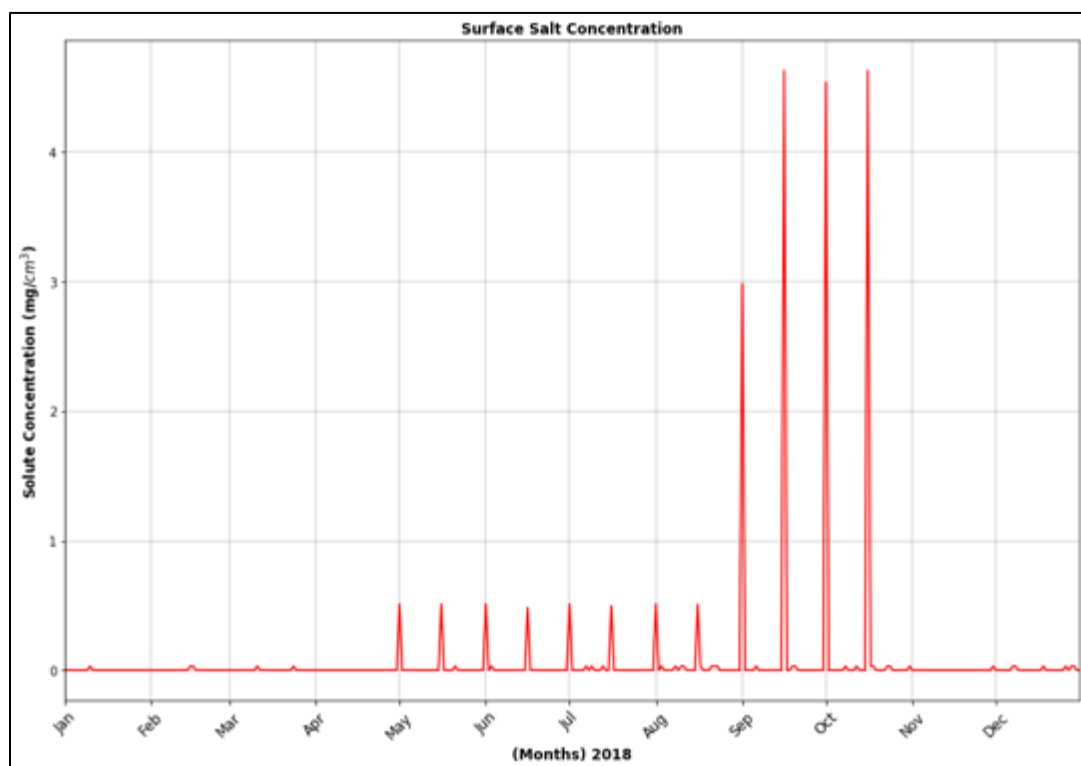
Figure 1. 9 – Surface Solute Concentration (mg cm-3)

26
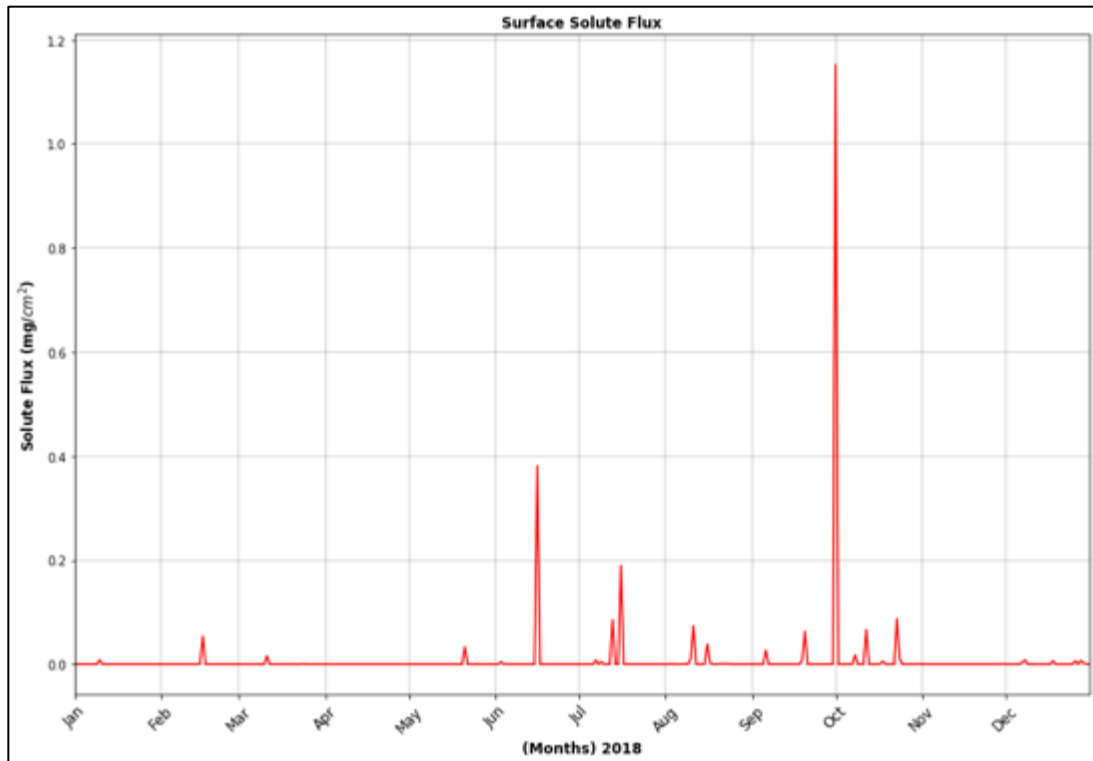
Figure 1. 10 – Surface Solute Flux (mg cm$_{-2}$ day $_{-1}$)

Pecan is a perennial crop and it is assumed to be fully grown throughout the entire simulation duration with variation in its canopy cover resulting in a T_p as shown in Figure 1.5. Cotton is an annual crop and therefore, its growing period is set from May to October with a specified K_c resulting in a stimulated T_p as shown in Figure 1.6. The threshold value of salt tolerance, EC_{50} of pecan is 3 dS/m (G. Ganjegunte & Clark, 2017) and cotton is 7.7 dS/m (Maas & Grattan, 1999).

5.2   Simulation Scenarios

In order to assess the model's capability to predict the effects of salinity stress in cotton and pecan, it is required to simulate and compare various scenarios. Therefore, the model has been run as per scenarios shown in Table 1.6 under different condition of stresses.

27

Table 1. 6 – Simulation Scenarios

Scenarios		Type of Stress (✓ Active)		
Pecan	Cotton	Osmotic Stress	Water Stress	Stress Type
P1	C1		✓	No Salinity Stress
P2	C2	✓	✓	Salinity Stress

Scenario P1, C1 simulates root water uptake with salinity stress response function set at 1, i.e., no salinity stress and zero solute transport in sector SL. This predicts the actual root water uptake by crops under water stress and having no salinity stresses.

In scenario P2, C2, the osmotic stress due to salinity is activated. This predicts the root water uptake by crops under salinity and water stress representing a real-world scenario where both stresses act in tandem.

The simulation scenarios are designated the way it is run in the model with P and C representing Pecan and Cotton, respectively. For visualization of the output data, it has been exported and plotted using Matplotlib in Python.

5.3   *Simulation Results*

The results of simulation are attributable to a nonlinear complex dynamic circular relation between water infiltration, solute transport and root water uptake. In order to understand the system dynamics, the results of each sector need to be interpreted acknowledging the interlink between them. In order to understand the correlation, the results are discussed in a sequence leading to root water uptake. For discussion purposes, simulation results for soil water storage, solute transport, α_s, and α_h are considered for simulation scenario P4, C4.

5.3.1   Soil Water Content

Infiltrated water is available to the crop from the water stored in each layer. The model simulates the water infiltration and predicts the water content in each layer as shown in Figure 1.11.
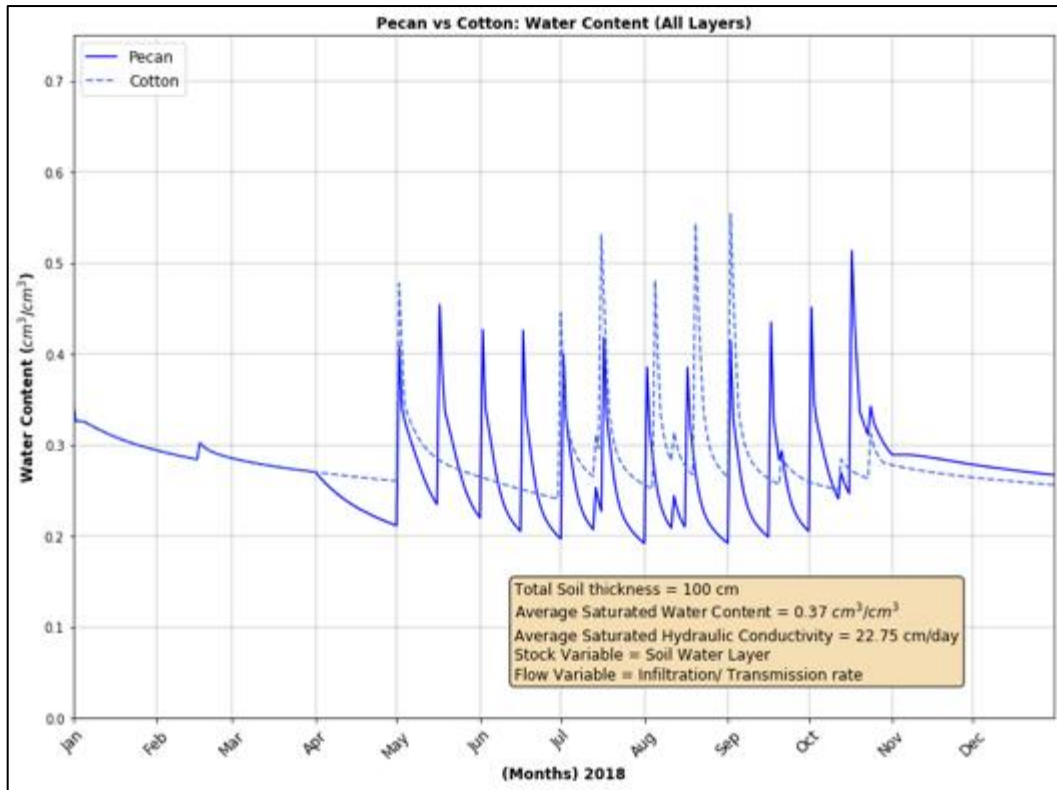
Figure 1. 11 – Water Content of Pecan and Cotton (All Layers)

5.3.2   Water Stress Response Function (αh)

Water stress occurs due to the scarcity of water to the plant during its growing period. It is expressed as a rating value αh between 0 and 1 representing maximum and no stress, respectively. αh is depended on the pressure head created by infiltrated water and soil water storage in the form of $\alpha(h) = \dfrac{1}{1+\left(\frac{h}{h_{50}}\right)^3}$. A comparison of αh for pecan and cotton as shown in Figure 1.12, shows that cotton is more prone to water stress than compared to pecan.
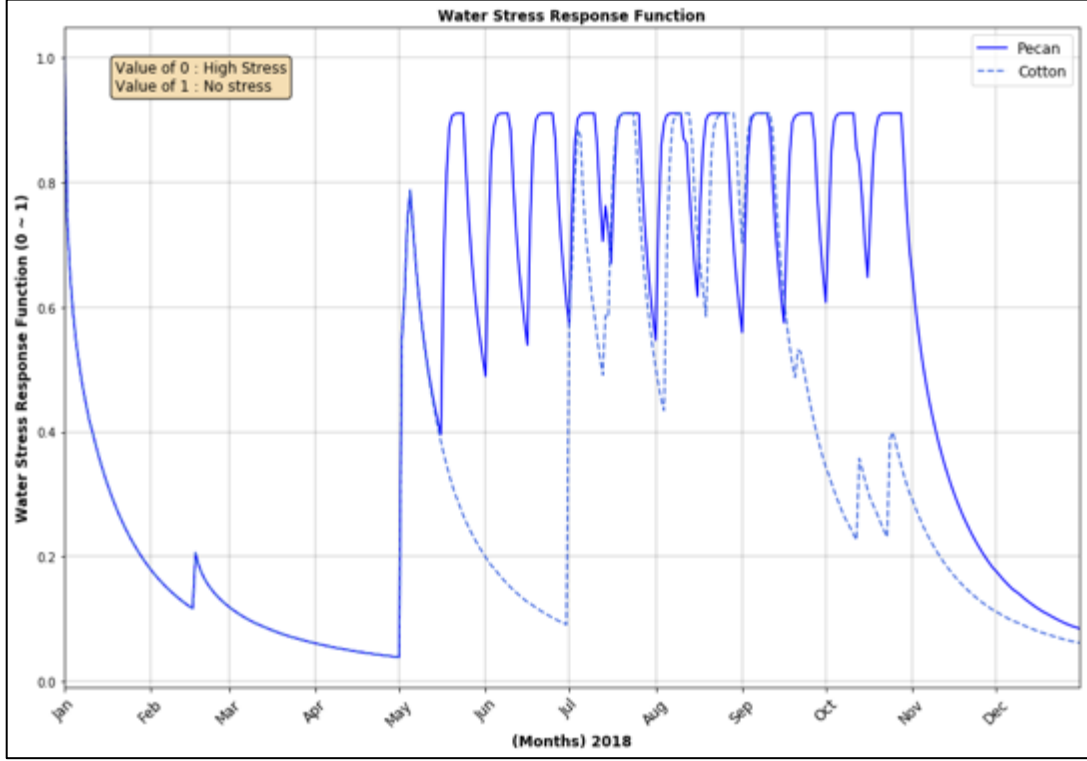
Figure 1. 12 – Water Stress response function for pecan and cotton

5.3.3 Solute Transport

The model simulates the transport of solute and predicts the solute concentration in the root zone at each compartment of 30 cm, 30 cm and 40 cm. Root zone solute concentration varies with layer for each crop as shown in Figure 1.13 and 1.14. These solute concentrations are in turn responsible for the salinity stress in crops in the form of $\alpha(s) = \dfrac{1}{1 + \left(\dfrac{EC}{EC_{50}}\right)^3}$ in each respective layer.
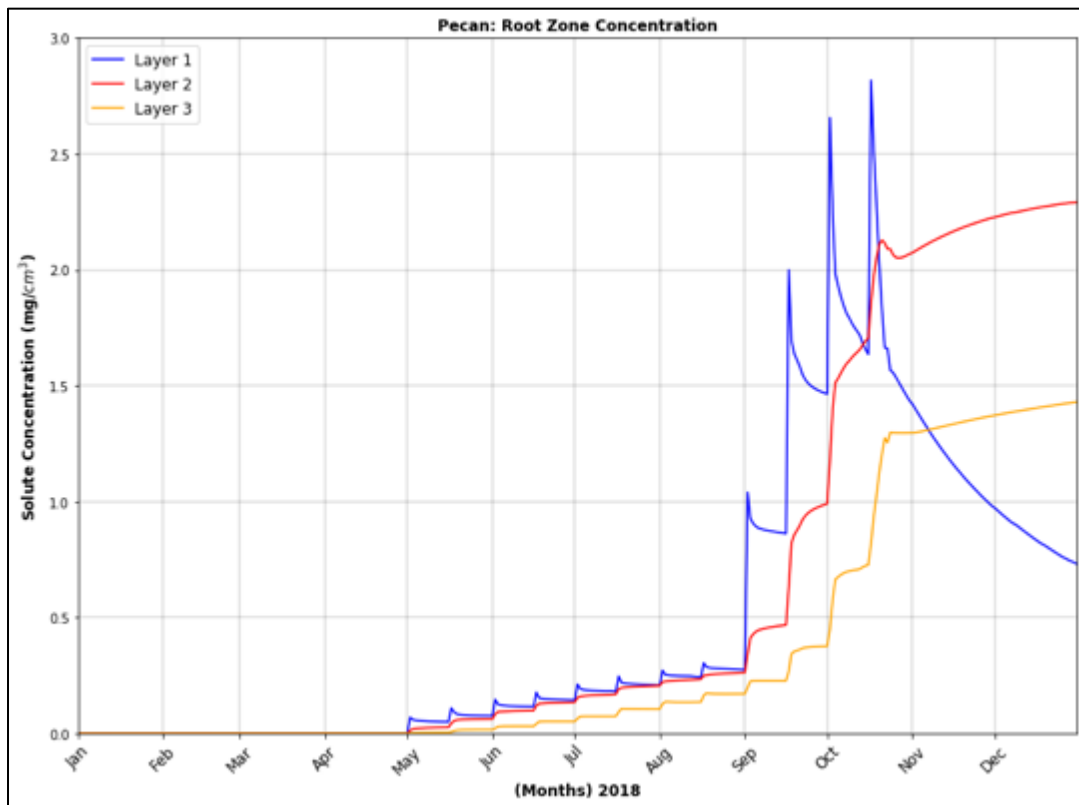
Figure 1. 13 – Comparison of Solute accumulation in each layer in Pecan
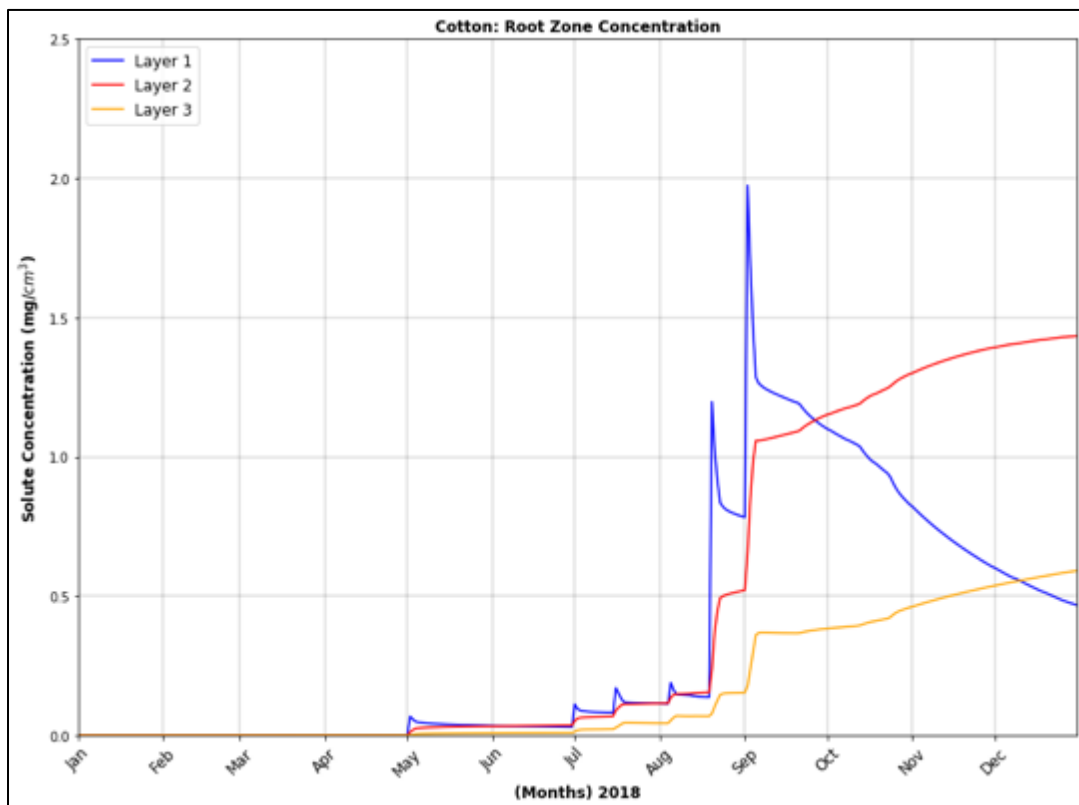
Figure 1. 14 – Comparison of Solute accumulation in each layer in Cotton

31

To better understand the salt accumulation, the cumulative solute concentration for the entire root zone is calculated by adding up all layers as shown in Figure 1.15. It is inferred that pecan has higher solute concentration than cotton given that solute is transported along with infiltrated water and the roots of crop extracting more water will have higher solute concentrated in their root zone. Since with its fully grown and longer roots extracts comparatively more water than cotton.
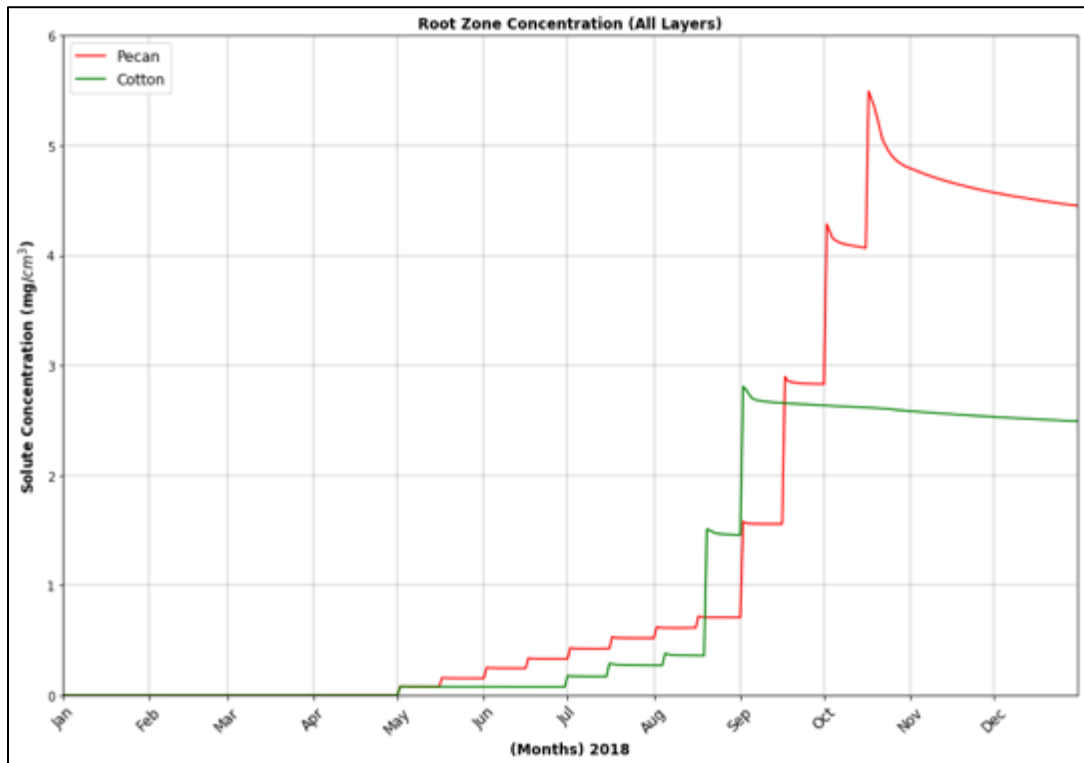
Figure 1. 15 – Comparison of Solute accumulation in pecan and cotton

5.3.4 Salinity Stress response function (α_s)

α_s is calculated dynamically with every Δt change in root zone solute concentration for each layer simulated in the solute transport sector and threshold values of their salt tolerance. It is expressed as a rating with value between 0 and 1 where 0 represents maximum stress and 1 represents no stress. The model prediction of α_s for cotton and pecan is shown in Figure 1.16 and 1.17.

Pecan being a low salt tolerant crop with a threshold value of 3 dS/m is expected to have comparatively higher α_s than the high salt tolerant variant cotton with a threshold value of 7.7 dS/m. The simulation results show a higher α_s varying between 0.6 to 1 for pecan and lower α_s varying between 0.983 to 1 for cotton.
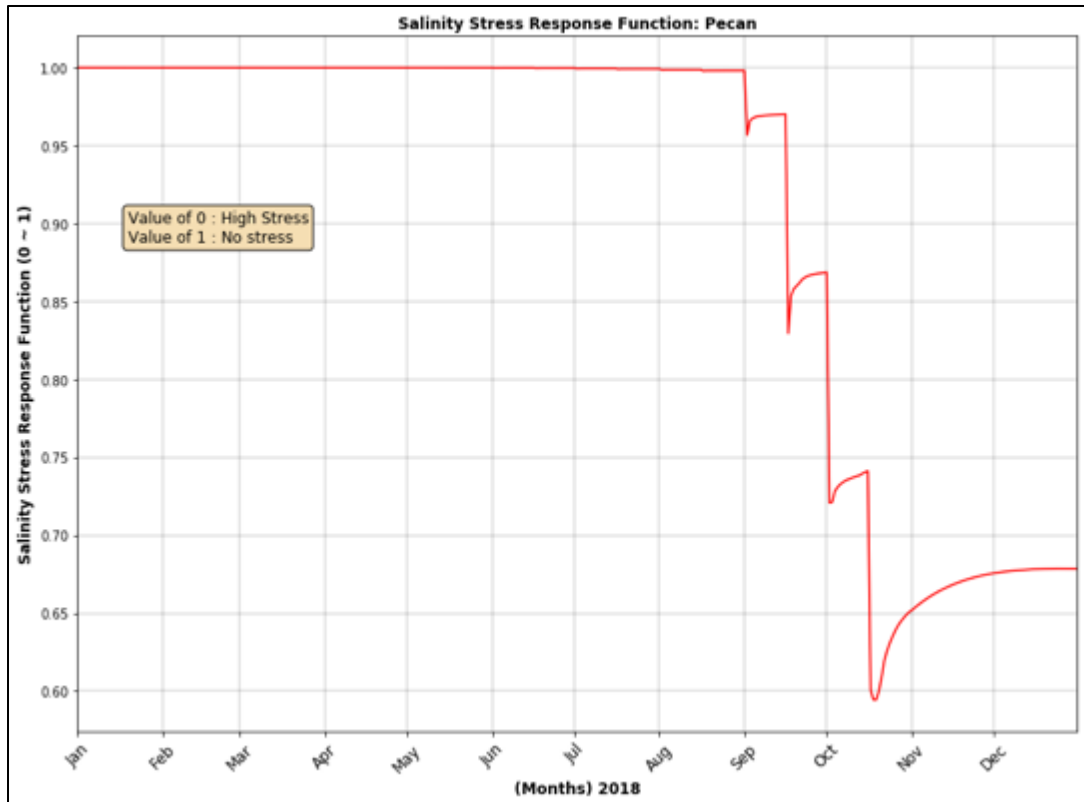
Figure 1. 16 – Salinity Stress response function for pecan
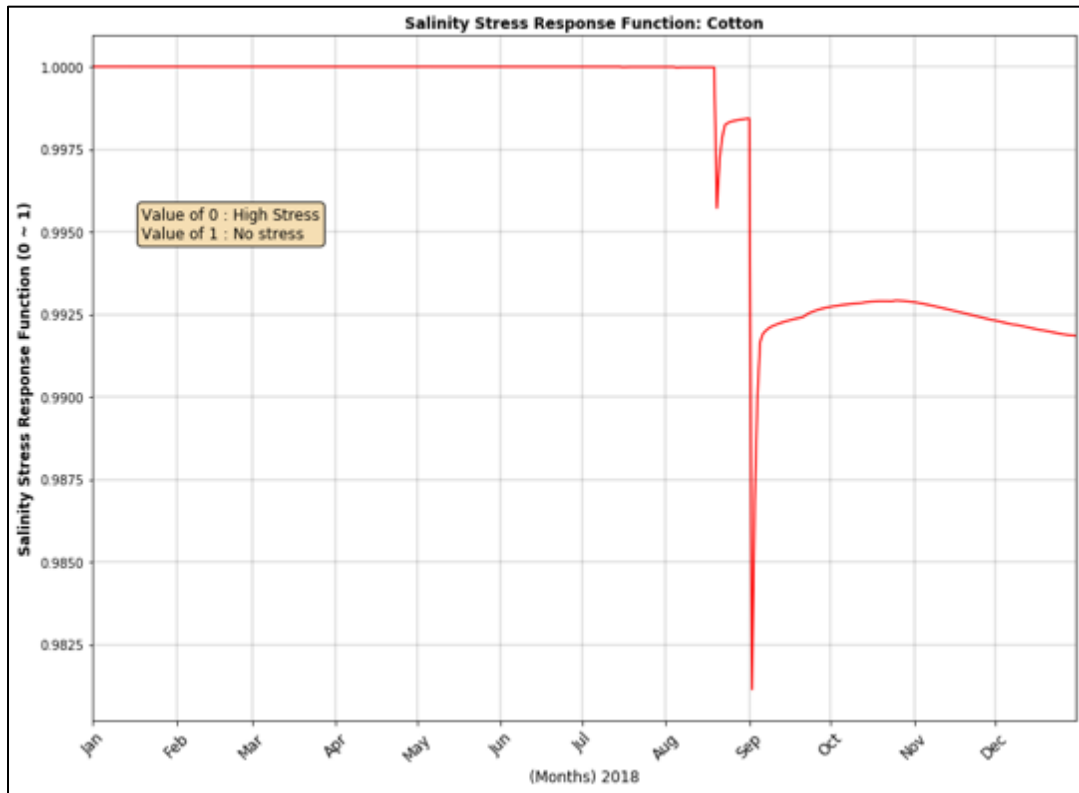
Figure 1. 17 – Salinity Stress response function for cotton

5.3.5 *Root Water Uptake*

The dynamics of root water uptake depends on the stored water in soil layer and solute transport in the form of rating values, α_s and α_h. The entire root water uptake in a soil depth of 100 cm is divided into compartments of 30 cm, 30 cm and 40 cm with each representing the actual root water uptake in respective layers. The total cumulative root water uptake for cotton and pecan is calculated by summing up value of all layers as shown in Figure 1.18 and 1.19.

Pecan, with α_s varying from 0.6 to 1, shows a reduction in root water uptake under salinity stress as it can been seen that P1 is greater than P2. Since the pecan has a low salt tolerance with a threshold value of 3 dS/m, it is prone to a salinity stress for a salt accumulation higher than 3 dS/m.

34
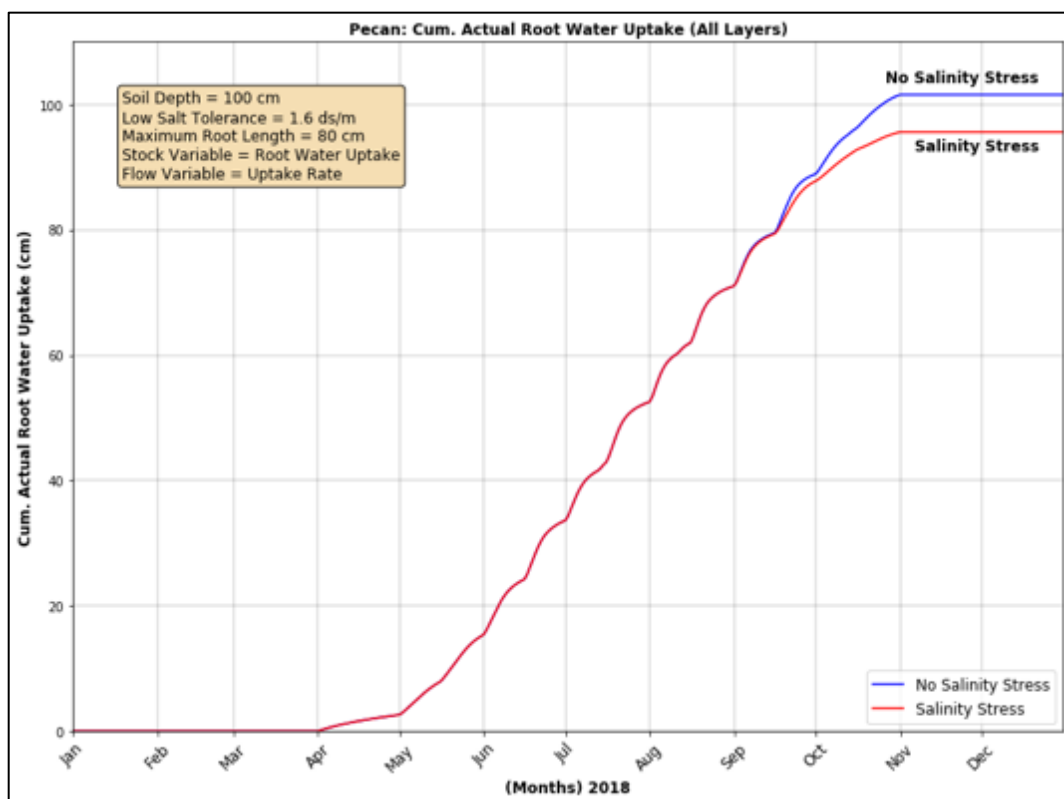
Figure 1. 18 – Comparative cumulative actual root water uptake of pecan under different stresses
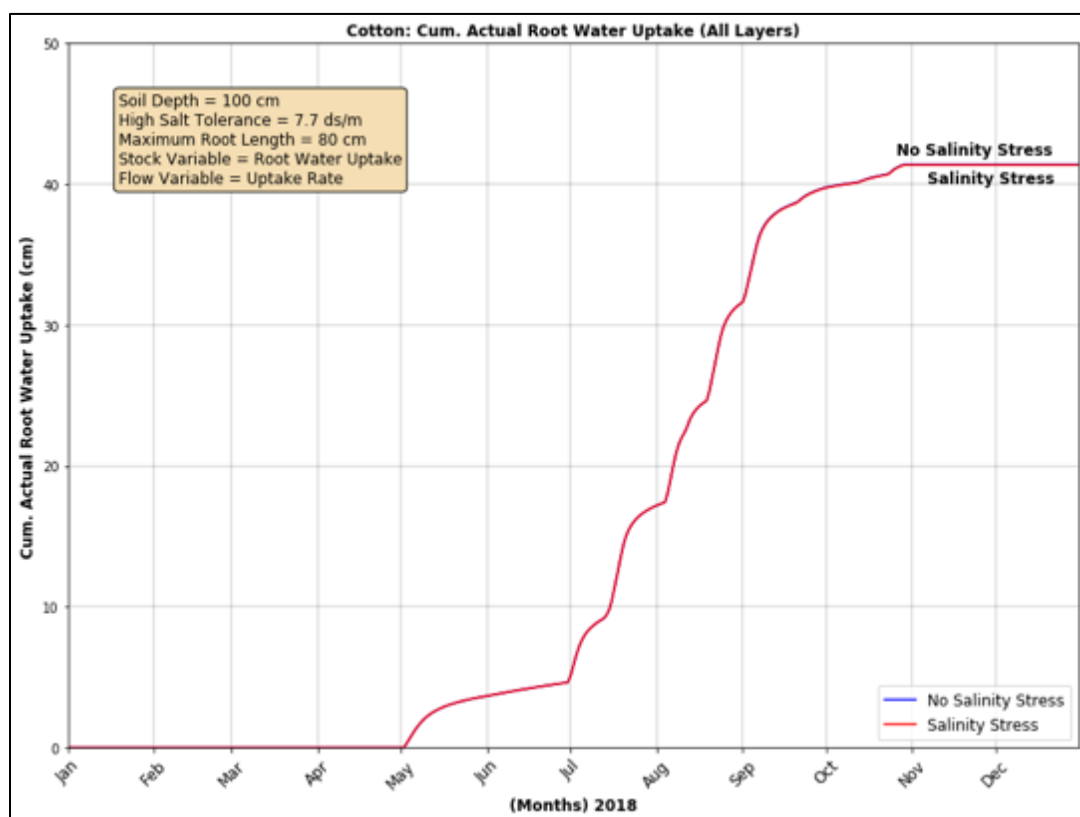
Figure 1. 19 – Comparative cumulative actual root water uptake of cotton under different stresses

35

Cotton, with α_s varying from 0.983 to 1, root water uptake under salinity stress (C2) is almost equal to that at no salinity stress (C1). This is due to the fact that cotton has a high salt tolerance threshold value of 7.7 dS/m and the salt accumulation is the root zone is lower than this value for the majority period in the year.

Root water uptake of cotton is expected to be comparatively lesser than pecan due to the fact that cotton is an annual crop with a lesser growing period. As expected, the model predicts the root water uptake of cotton lesser than pecan as shown in Figure 1.20. Simulation scenario P2, C2 comprising of salinity and water stress is simulated for comparison of pecan and cotton, respectively.
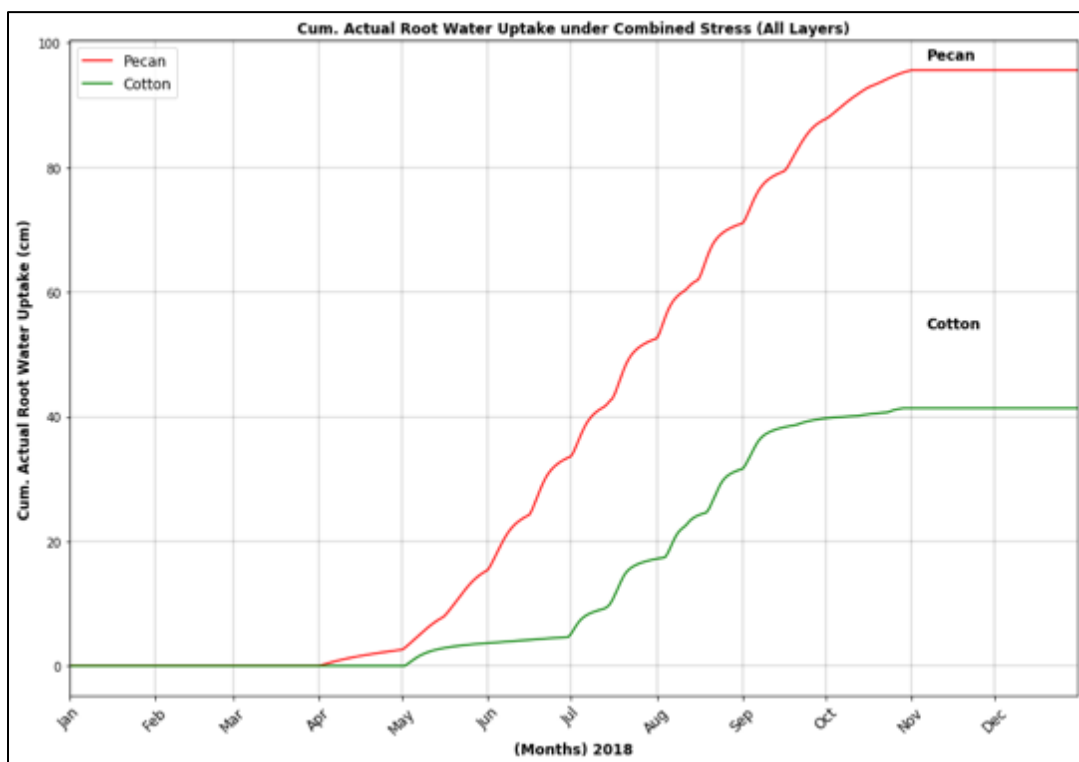
Figure 1. 20 – Comparative cum. actual root water uptake for pecan and cotton for combined stress

A closer look at the simulation results confirms the fact that for cotton, the root water uptake peaks from May to June when its lateral root density is the maximum. Whereas for pecan,

the root water uptake increases gradually since its root distribution is uniform throughout the year.

This shows that the model was successful in predicting the root water uptake in the absence and presence of stresses for cotton and pecan separately. Also, the prediction of root water uptake for pecan and cotton shows the variation as observed in perennial and annual crop.

5.3.6 *Water Balance*

Water balance of a system is the amount of water flowing in and out of the soil column. Water balance of the soil column of this study is given by:

$$Water\ Applied\ =\ Root\ water\ uptake + Leached\ Water + Soil\ Water\ Storage \quad 37$$

The calculated water balance equation for the soil column is shown in Figure 1.21.
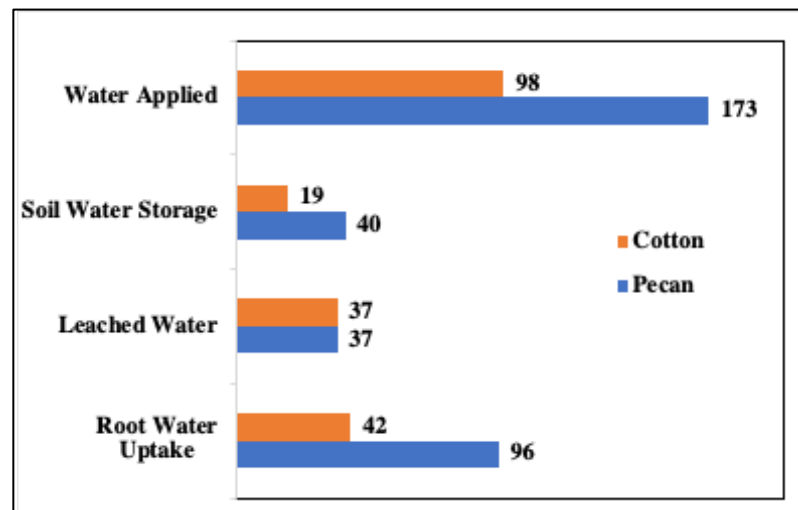
Figure 1. 21 – Water Balance for Pecan and cotton for all layers with water depth in cm

From the water balance under salinity stress, it is observed that pecan extracts about 96 cm of water out of the applied 173 cm adding up to 55%. As for cotton, it extracts 42 cm of water out of the applied 98 cm adding up to 43%. It can be seen that both pecan and cotton have the similar amount of water leached out. Pecan with its perennial and fully-grown roots is capable of extracting more water from the soil than cotton.

5.4   Comparison of results with HYDRUS

The model's prediction can be categorized as the numerical solutions derived from the finite difference equation using system dynamics. Numerical solutions are approximate estimation demonstrating a real-world problem. One of the methods for verification of these solutions in an accurate, comprehensive, exhaustive, efficient and cost-effective manner is to compare with a similar mathematical model (Abelman & Patidar, 2008; Haverkamp, Vauclin, Touma, Wierenga, & Vachaud, 1977; Shawagfeh & Kaya, 2004).

HYDRUS solves infiltration, solute transport and root water uptake using finite element approximation. In order to represent the system dynamic model in in HYDRUS, the soil profile of 100 cm was divided into 30, 30, and 40 cm using 4 nodes. The hydraulic properties for three layers, node 1 to 2 was selected as material 1, node 2 to 3 as material 2 and node 3 to 4 as material 3 representing the three soil compartments of 30 cm, 30 cm and 40 cm, respectively.

Data for rainfall, surface solute concentration, transpiration, root length and soil hydraulic properties has been inputted same as the system dynamic model. In the system dynamic model, hydraulic conductivity is reduced to almost 50% of its value throughout the simulation due to the effects of hydraulic reduction function and therefore, K_s for HYDRUS was set at 50% of the value for each layer.

HYDRUS modules for soil water flow, standard solute transport, root water uptake and root growth were chosen with a simulation duration of 365 days. The simulation results for cumulative actual root water uptake, actual uptake rate and root zone solute concentration of pecan and cotton has been compared with the system dynamic model as shown in Figure 1.22, 1.23, 1.24, 1.25, 1.26 and 1.27.
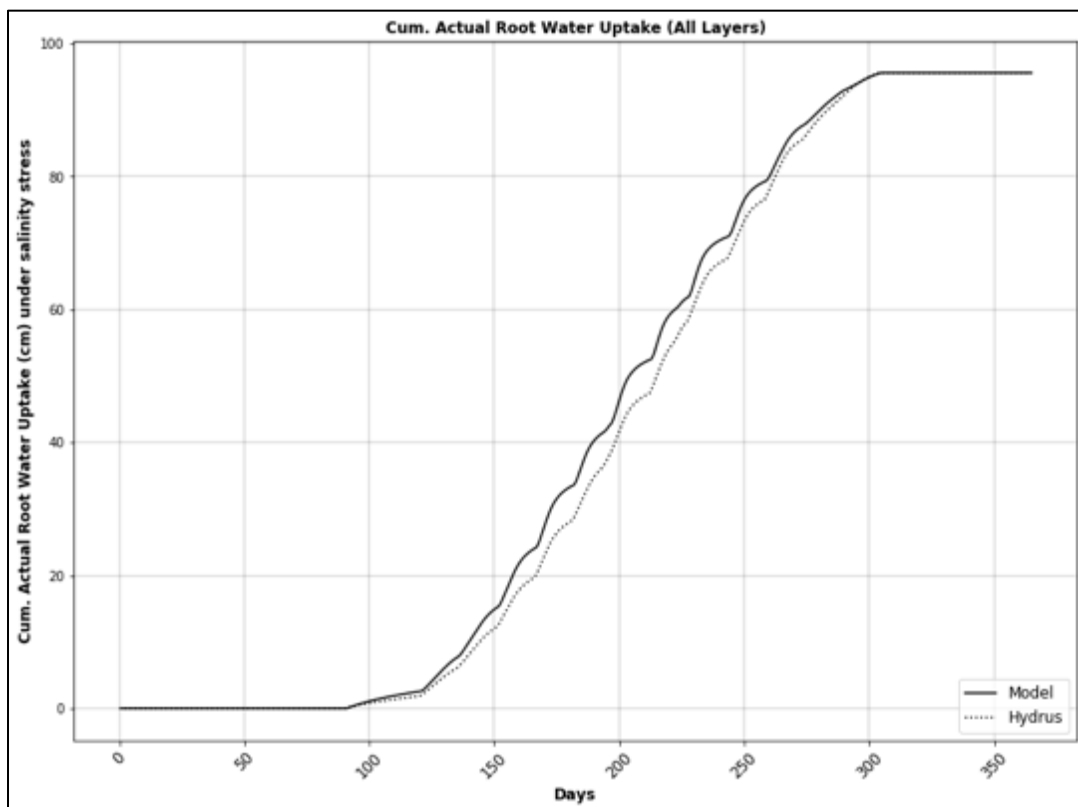
Figure 1. 22 – Comparison model results with Hydrus: cum. Actual Root water uptake for pecan
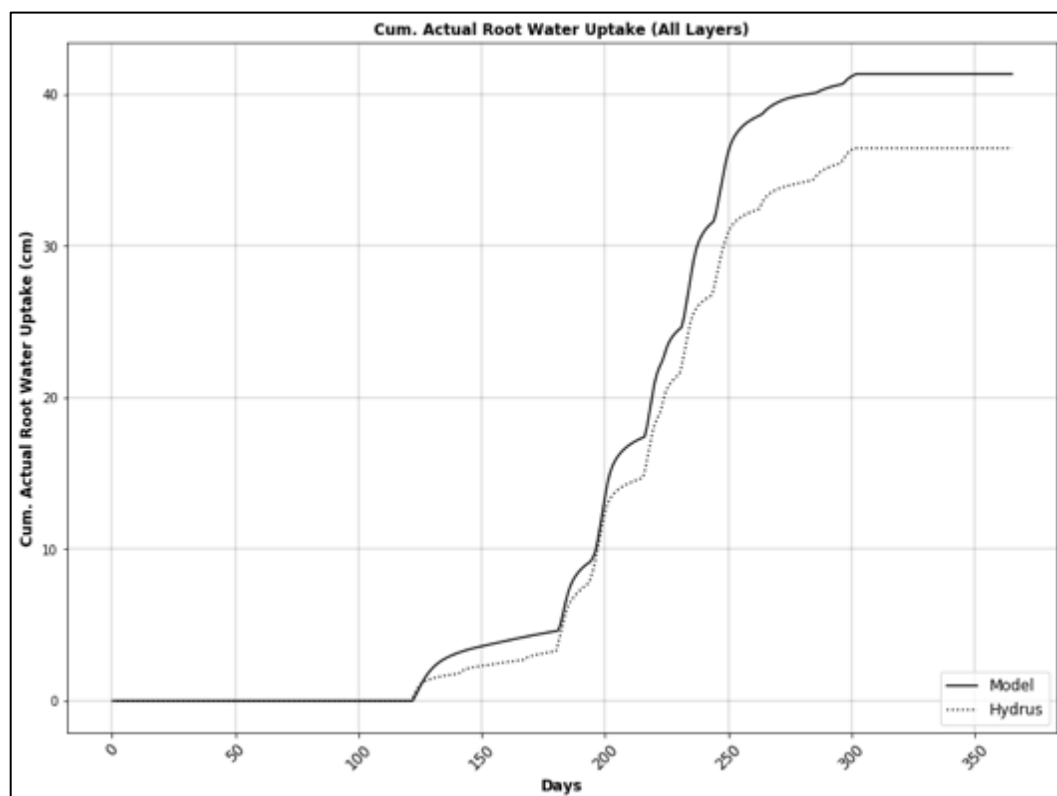
Figure 1. 23 – Comparison model results with Hydrus: cum. Actual Root water uptake for cotton
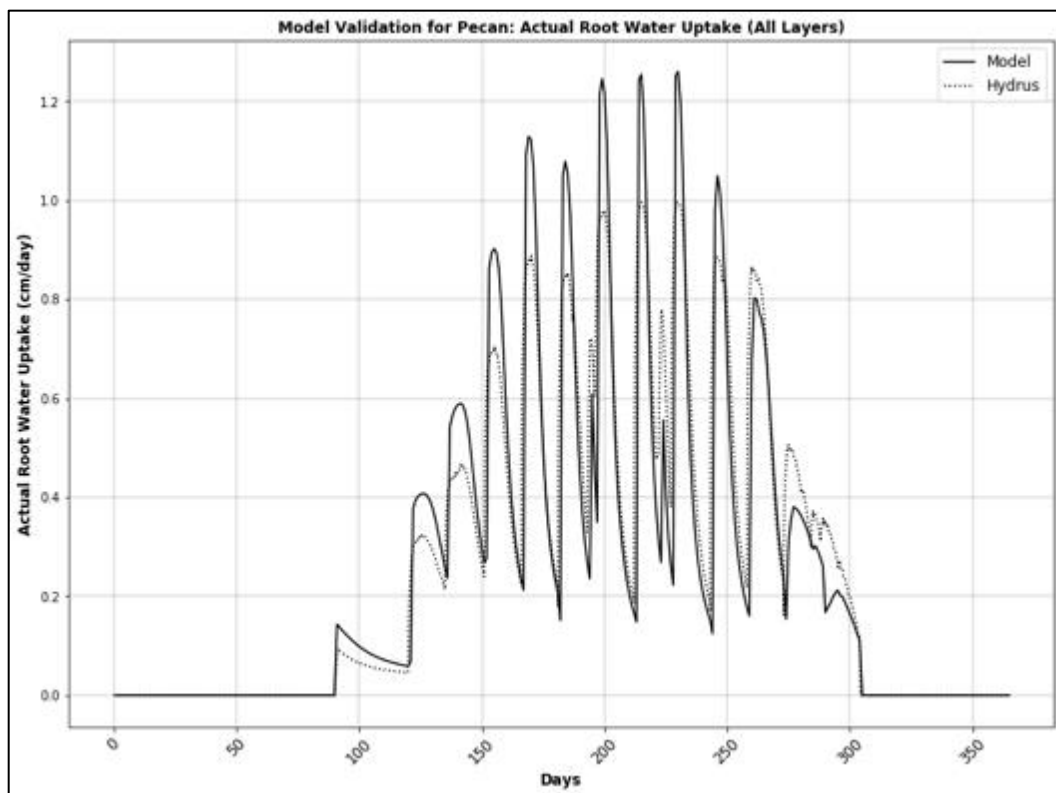
Figure 1. 24 – Comparison model results with Hydrus: Actual Root water uptake for pecan
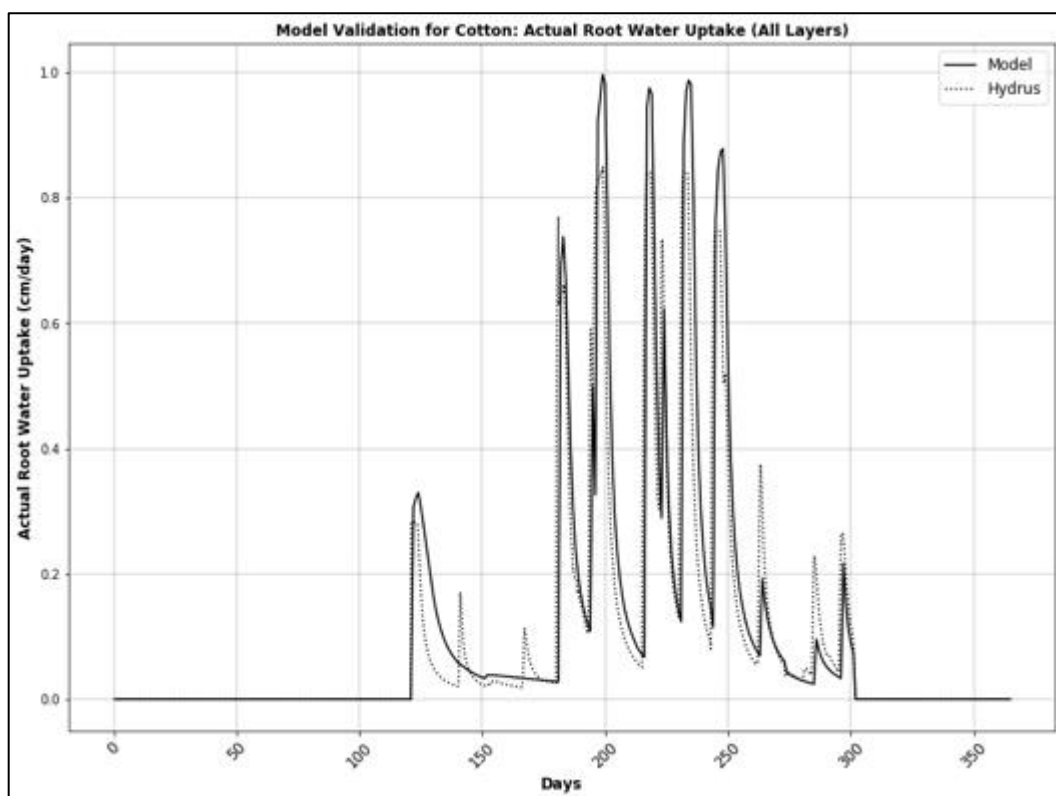
Figure 1. 25 – Comparison model results with Hydrus: Actual Root water uptake for cotton

40
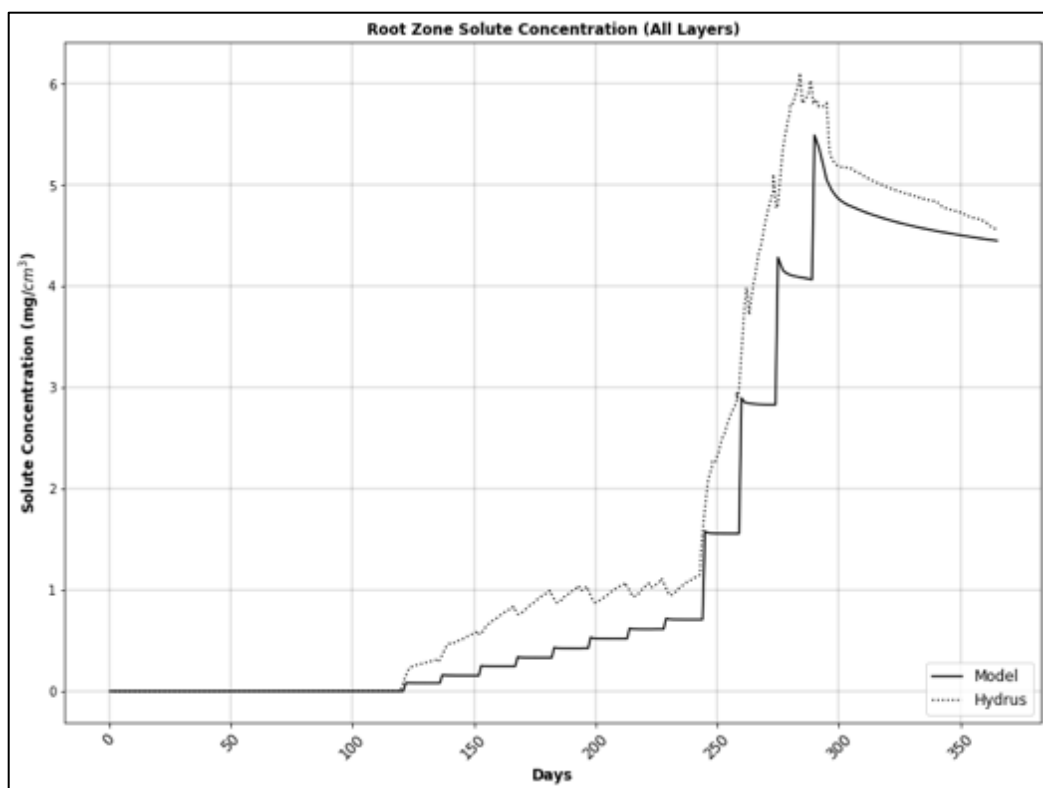
Figure 1. 26 – Comparison model results with Hydrus: cum. Root zone solute concentration for pecan
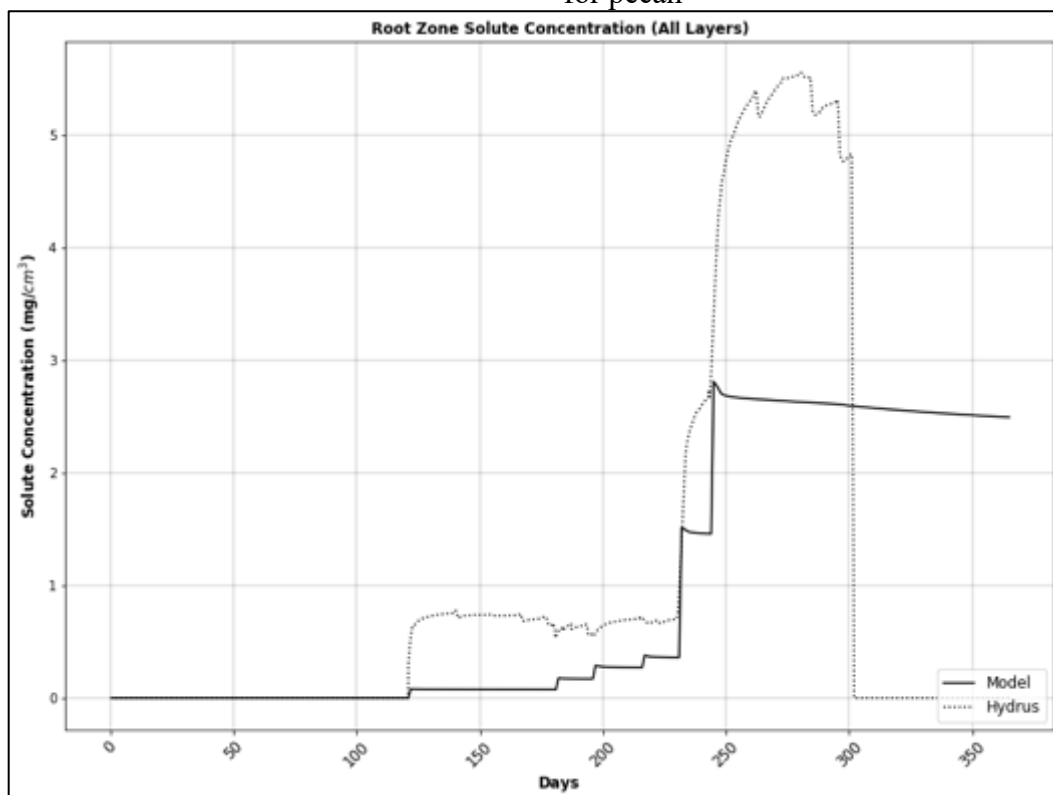
Figure 1. 27 – Comparison model results with Hydrus: cum. Root zone solute concentration for cotton

5.4.1   Data Analyzes of Results

The consistency of the results simulated by the model in comparison with HYDRUS is further evaluated by computing the Root Mean Square Error (RMSE) and Pearson's correlation coefficient, R & R_2:

$$RMSE \;=\; mean\;(X-Y)^{1/2} \qquad\qquad 38$$

$$R \;=\; covariance(X,Y)\,/\,(stdv(X)*stdv(Y)) \qquad\qquad 39$$

where, X and Y are the simulated value for the ith observation from HYDRUS and the Model. The calculated RMSE and R value for the cumulative actual root water uptake and root zone solute concentration is shown in Table 1.7.

Table 1. 7 – RMSE and R

Parameters	RMSE		R		R_2	
	Pecan	Cotton	Pecan	Cotton	Pecan	Cotton
Cumulative Actual Root Water Uptake (cm)	2.810	3.317	0.999	1.000	0.996	0.957
Actual Root Water Uptake (cm/day)	0.104	0.517	0.926	0.879	0.837	0.705
Root Zone Solute Concentration (mg/cm3)	0.548	1.497	0.981	0.573	0.927	0.317

The model's prediction for pecan has small RMSE and high R and R_2 demonstrating that the model has predicted results similar to HYDRUS. The prediction for cotton is having a slightly higher RMSE of 3.317 cm, 0.517 cm/day and 1.497 mg/cm3; and R_2 of 0.957, 0.705 and 0.317 demonstrating that the model has slightly overestimated the root water uptake and uptake rate; and underestimated the root zone solute concentration. This is attributing the fact that pecan had a constant root length whereas cotton had variable root growth and thus, the normalized root distribution for cotton might have differed resulting in the variation in results. Overall performance

of the model shows that the simulation of soil water infiltration, solute transport and root water uptake under salinity and matric stress is conforming to the simulation results of HYDRUS.

The model's prediction for pecan has small RMSE and high R demonstrating that the simulation has accurately predicted in line with the HYDRUS simulation. The prediction for cotton is having a RMSE of 0.103 cm and 1.293 mg/cm$_3$ and R$_2$ of 0.854 and 0.533 demonstrating that the model has slightly overestimated the root water uptake and underestimated the root zone solute concentration compared to HYDRUS. This is attributing the fact that pecan had a constant root length whereas cotton had variable root growth and thus, the normalized root distribution for cotton might have differed resulting in the variation in results. Overall performance of the model shows that the simulation of soil water infiltration, solute transport and root water uptake under salinity and matric stress is conforming to the simulation results of HYDRUS.

6.0   Conclusion

A system dynamic model was developed for soil water infiltration, solute transport and root water uptake by numerically solving one dimensional Richard's equation and advection – diffusion equation based on finite difference approach along with other physical based formulations and empirical assumptions to evaluate the effects of salinity and matric stress on crops. The model simulated similar results to those from a finite element method based numerical model, HYDRUS. The operation and structure of the model is easily perceptible and adaptable, and a user can easily change the variables and parameters according to a project specific requirement without prior knowledge of any programming language. The accuracy of simulation result can be increased by adopting a site measured values for θ_r, θ_s, K_s, α, n, surface solute concentration, transpiration and controlled environment values for K_c and $\beta(z)$. The simulated results show that the salinity and water stress reduce the efficiency of crops to extract water from

the soil layer due to accumulated salt in the root zone. Under salinity stress, pecan is able to extract 55% of the applied water whereas cotton extracts 43% of the applied water; and about 20 ~ 30% of the water is either leached out or stored as soil water. These extraction capacities can be increased by practicing better irrigation management technique to reduce salt accumulation such as salt leaching and gypsum.

Section 2 – Evaluating Simulation Results for 10 Years

1.0   Introduction

Water in the arid South-West United States is mostly contains a significant concentration of dissolved salts. The main causes of salinity include the topography, surface water hydrology, minerals in underground water, low rainfall, high temperature, evaporation, extreme hot and dry winds and human factors such as irrigation and use of fertilizers (Naeimi & Zehtabian, 2011). When saline water is used for irrigation, it results in accumulation of salts in the subsurface soil.

El Paso is an arid region in the south west of United States in Chihuahua desert. Most of the irrigation water for the region is from Rio Grande river and ground water wells. Both sources based on the location have significant dissolved salts. The well water in El Paso contains 4 times as much salt as compared to average Rio Grande river and irrigation using well water increases leaching requirement by 30% (Miyamoto, 1982). Pecan and cotton are the major crops in the region. Many studies have focused on the irrigation efficiencies for cotton and pecan in the region (G. Ganjegunte & Clark, 2017; G. K. Ganjegunte et al., 2018; Miyamoto, 1982). These studies are based on field studies that are time consuming and require extensive monitoring. With the goal of determining water use efficiency, and salt-buildup numerical models will be both cost effective and time efficient.

Numerous numerical models are available for analyses of salt accumulation in the soil layers such as ENVIRO-GRO (Pang & Letey, 1998), SALTMED (Ragab, 2002), SWAP (van Dam, 2000), UNSATCHEM (Šimůnek et al., 1996; D. L. Suarez & Šimůnek, 1997) and HYDRUS (Šimůnek, J. et al., 1998, 2005; Šimůnek et al., 2013; Vogel et al., 1996). These models predict the salt accumulation based on numerical solution to physically based formulations and empirical assumptions. In addition to the simulation of salt accumulation, HYDRUS and UNSATCHEM

have an additional option for precipitation and dissolution of calcite, gypsum, nesquehonite, hydromagnesite and sepiolite that introduces the concept of amendment to the soil for reducing the accumulated salts (Šimůnek et al., 1996).

With increasing drought like conditions, the accumulation of calcium carbonate and other soluble salts rapidly increases in the soil. This occurs due to the continuously low rainfall in arid regions resulting in substantially less effective leaching of salts. The objective of this study is to simulate a system dynamic model to quantify the salt accumulation in the soil layer with irrigation water containing different salt concentration for a 10-year period of lowest rainfall recorded in El Paso region. The model will also predict the variation in root water uptake in cotton and pecan for different irrigation water.

2.0   Site Specific Data

In order to understand the issue of salt buildup in soil, the system dynamic model require site specific data for accuracy in prediction.

2.1   Site Selection

Texas A&M Agrilife Center at El Paso commercially manages sites at El Paso and Socorro for monitoring and assessing the effects of salinity in cotton and pecan production. For this simulation study, data was obtained for a 16 Ha area located at 31°30'32.30" N, 106°13'25.49" W of these commercial managed site. This region is classified as arid region with a low average annual precipitation of 15 cm and potential evapotranspiration of 194 cm; daily maximum and minimum temperatures of 35.8_oC and -3.4_oC; solar radiation of 19.78 MJ m_{-2} d_{-1} and wind speed of 1.21 ms$_{-1}$ (G. K. Ganjegunte et al., 2018).

2.2   *Soil Dimensioning*

Numerical model such as HYDRUS uses finite element method to predict the salt accumulation by dividing the entire soil depth into nodes of 1 cm each. This allows solute potential gradients to exist within the layers and increase solute transport rate in the profile. Similarly, the system dynamic model requires the soil to be divided into layers to create gradients for solute transport. The simulation in the study site is for a subsurface soil column of 100 cm depth and unit area of 1 cm2. The entire soil depth is divided into three layers of 30 cm, 30 cm and 40 cm. The model will simulate the salt transport and predict the salt accumulation in each layer. Consequently, the corresponding root water uptake will be predicted allowing the comparison of effects of root water uptake for different irrigation water.

2.3   *Soil Physical and Chemical Properties*

Field and laboratory estimation of the soil physical and chemical properties various soil types will be costly. The soil hydraulic properties, θ_r, θ_s, and K_s for the 16 Ha study site was obtained from Web Soil Survey consisting of Tigua (Tg - 72%), Glendale (Gs - 12%) and Harkey (Hs - 16%) silty clay loam soils as shown in Figure 2.1. The air entry pressure, α (cm-1) and pore size distribution, n of the Soil Water Retention Curve was not readily available.

Schaap & Van Genuchten, 2006 classified and evaluated soil across United States determining the soil hydraulic properties. Soil in the study site is classified as silty clay loam and a value of 0.0178 cm-1 for α and 1.30 for n has been adopted from this study (Schaap & Van Genuchten, 2006). The soil hydraulic properties for the simulation is given in Table 2.1.

Figure 2. 1 – Soil Map at (31°30'32.30" N, 106°13'25.49" W) in El Paso County, Texas

Table 2. 1 - Soil Hydraulic Properties (Resize)

Soil depth (from Topsoil) (z) cm	Residual Water Content (θ_r) cm3 cm-3	Saturated Water Content (θ_s) cm3cm-3	Saturated Hydraulic Conductivity (K_{sat}) cm day-1	Soil pH	Maximum Water Holding Capacity (cm) ($z \times \theta_s$)
30	0.00	0.34	6.11	8.15	10.2
30	0.01	0.39	15.80	8.15	11.7
40	0.02	0.39	40.44	8.15	15.6

3.0 Time varying boundary conditions

El Paso experienced historical droughts from year 1950 to 1956 (Manford, Dixon, & Dent, n.d.). As decreasing rainfall increase salt accumulation, the simulation duration of the system dynamic model was set for a period of 10 years from 1947 to 1956.

3.1   *Rainfall*

A data analyzes of rainfall records showed that these periods recorded the lowest rainfall in El Paso. The rainfall data for the period was downloaded from Climate Data Online (CDO), National Climatic Data Center (NCDC) as shown in Figure 2.2. The simulation duration was set for 3653 days and the model calculated each variable for every 0.125 of a day.
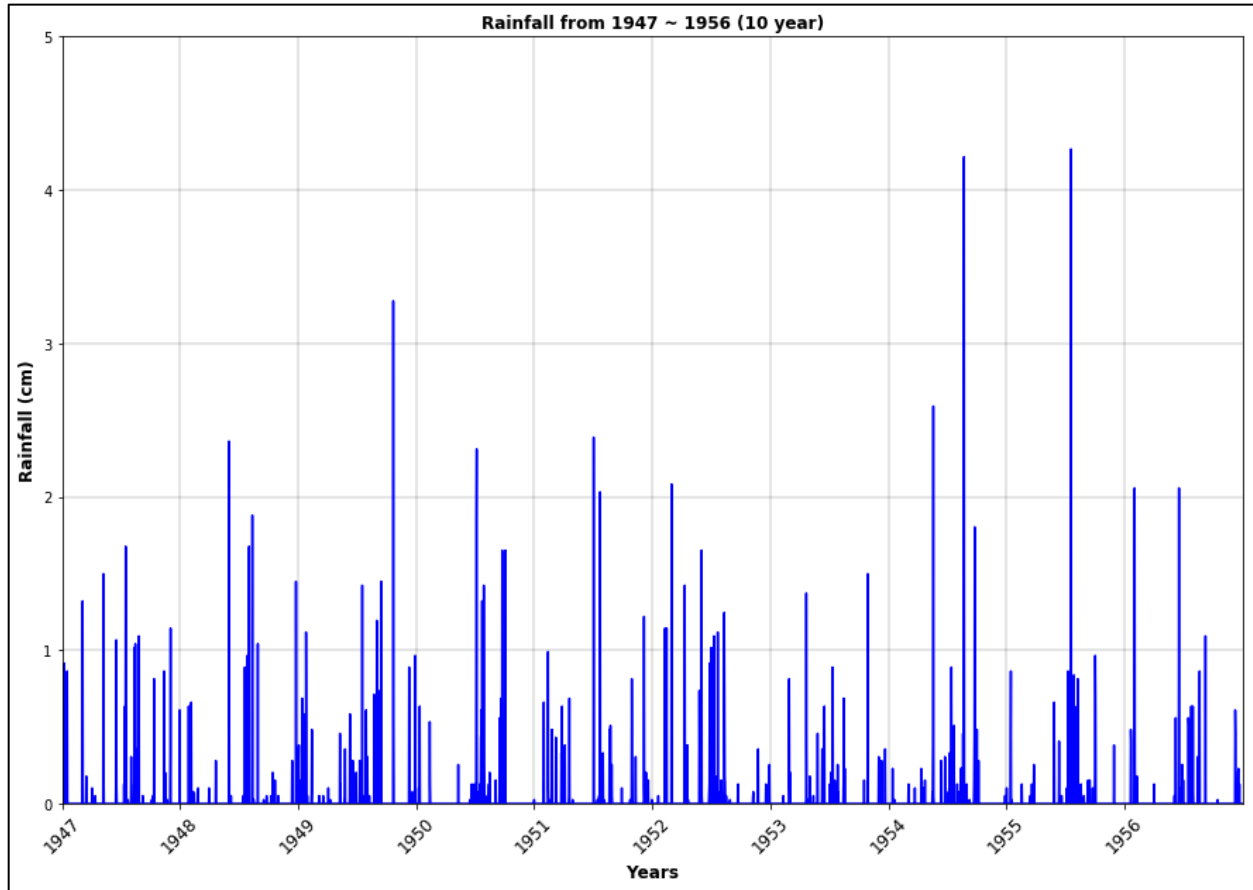
Figure 2. 2 – Daily rainfall for 10 year from 1947 to 1956

3.2   *Irrigation Water*

Salinity of water depends upon the type of water used for irrigating the crop. As water from ground wells will be higher than river or rainwater, the source of irrigation will adversely affect the salt accumulation in the soil layers. The irrigation cycle of cotton and pecan is as given in

Table 2.2. It is assumed that cotton and pecan is irrigated with the same frequency throughout the period from 1947 to 1956.

Table 2. 2 - Irrigation Cycle for a year

Month	Day	Irrigation Water (cm)
Pecan		
May	01	12.7
	16	12.7
June	01	12.7
	16	12.7
July	01	12.7
	16	12.7
August	01	12.7
	16	12.7
September	01	12.7
	16	12.7
October	01	12.7
	16	12.7
	Total	**152.4**
Cotton		
May	01	12.7
June	30	12.7
July	15	12.7
August	04	12.7
	19	12.7
September	01	12.7
	Total	**76.2**

The source of irrigation water is chosen for different simulation based on the salt content. Rainwater supplements irrigation whenever the region has received rainfall. Irrigation using groundwater will increase the salt content compared to river water. Therefore, five different mixture of irrigation and ground water with different percentage of contribution is generated. It is ranked from highest to the lowest based on salt content as given in Table 2.3.

Table 2. 3 - Combination of Irrigation Water (River water and Groundwater)

Water Type	Salt Content	River water (%)	Groundwater (%)
Water 1	Highest	0	100
Water 2	High	30	70
Water 3	Medium	50	50
Water 4	Low	70	30
Water 5	Lowest	100	0

3.3   *Surface Solute Concentration*

As important as the rainfall, the surface solute concentration is significant to kick start the simulation of the model from an initial condition. The daily load of salt in rain, river and groundwater need to be inputted for a period of 10 years creating a dataset of 3653 points. Due to the non-availability such extensive data, the surface solute concentration is generated for different combination of irrigation water based on initial day's solute concentration as given in Table 2.4. It is further assumed that salt is added every year to the groundwater by an amount 4.48 mg/l.

Table 2. 4 - Day 1 Salt Concentration in Irrigation Water (mg/l)

Salt Type	Total Dissolved Salts	Sodium	Calcium	Magnesium
Rainwater (SR)	32	10.95	19.2	1.77
River Water (SRW)	512	106.94	101.38	16.52
Ground Water (SGW)	4627.2	1941	252	59.52

The effective solute concentration entering the system dynamic model as initial condition for each day from 1947 to 1956 is given by:

$$S_i = \frac{R_i \cdot SR_i + RW_i \cdot SRW_i + GW_i \cdot SGW_i}{R_i + RW_i + GW_i}$$ 1

where, i stands for ith day.

3.4 Evapotranspiration

The daily potential evapotranspiration has been calculated from the average monthly data of El Paso for last 52 years from Texas ET Network as shown in Table 2.5.

Table 2. 5 – Average ET_0 (cm/month)

Month	ET_0
January	7.0
February	9.0
March	15.4
April	20.8
May	25.0
June	28.2
July	23.3
August	22.7
September	19.5
October	15.0
November	9.1
December	6.3

The consumptive value K_c for pecan has been calculated from (Miyamoto, 1982) and cotton from (Phocaides, 2000). The crop evapotranspiration (T_p) is calculated by equation given by:

$$T_p = K_c \, ET_0$$ 2

4.0   Crop Data

Due to the popularity of pecan and cotton in the region, these crops are selected for assessing the effects on its ability to uptake water from these salt accumulated layers. Cotton is a highly salt tolerant crop with a threshold electric conductivity (EC) value of 7.7 dS/m implying that the cotton doesn't have any effect of salinity stress until it reaches the threshold value (Maas & Grattan, 1999). Similarly, the threshold EC value of pecan is 3 dS/m implying that it is a low salt tolerant crop. Both the crops are expected to reach its 50% water extraction potential at a capillary pressure gradient of -150 cm for pecan and -50 cm for cotton. In addition, the model requires time varying conditions of the crop such as root length and normalized root distribution function over the growing period.

4.1   Root Length

The root length for pecan is assumed to be constant at 80 cm and cotton is assumed to be linear according to the locally observed root length for irrigated cotton at El Paso for a growing period of 180 days as shown in **Table 2.6.**

Table 2. 6 – Cotton Root Length (cm)

Length (cm)	Crop Period (days)
0 - 25	0 – 20
25 – 40	21 – 30
40 – 75	31 – 50
75	51 - 180

4.2   Percentage Root Distribution (β)

Percentage root distribution for cotton has been calculated form the root length density value from (Zhi et al., 2017) as shown in Figure 2.3.
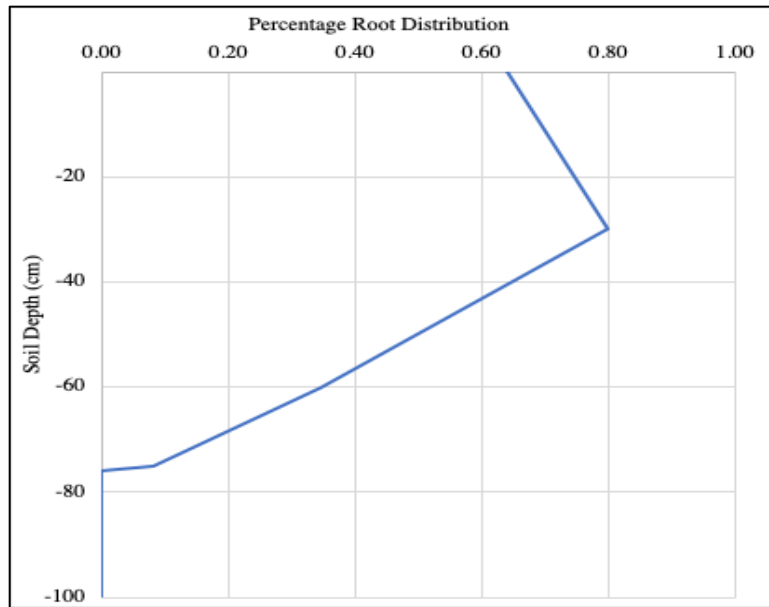
Figure 2. 3 – Percentage Root Distribution for Cotton

The roots of pecan are considered to be fully grown at the time of simulation having a span of 300 cm on either side and a total root length of 80 cm. As a result, the root length and normalized root distribution function does not vary with time during the entire simulation period. The Percentage root distribution is calculated from the root dimensions given in (Woodroof & Woodroof, 1934) and as shown in Figure 2.4.
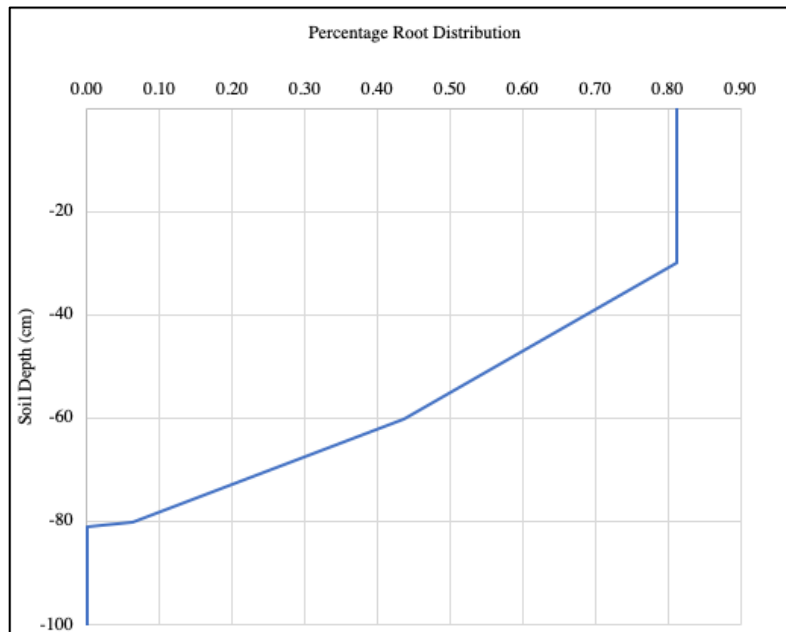
Figure 2. 4 – Percentage Root Distribution for Pecan

5.0   Results and Discussion

The simulated results infer the effect of different source of irrigation water in root water uptake of cotton and pecan. The system dynamic model allows the user to have multiple simulation with option for comparison in the form of graphs. Table 2.7 shows the simulation scenarios chosen for pecan and cotton as designated in the system dynamic model.

Table 2. 7 - Simulation Scenario

Water Type	Salt Content	Simulation Runs		River water	Groundwater
		Pecan	Cotton	(%)	(%)
Water 1	Highest	P1	C1	0	100
Water 2	High	P2	C2	30	70
Water 3	Medium	P3	C3	50	50
Water 4	Low	P4	C4	70	30
Water 5	Lowest	P5	C5	100	0

Simulation results are plotted for solute concentration in root zone, salinity stress response function (α_s) and root water uptake for different concentration of saline water.

5.1   Salt Accumulation in Root Zone

Salt transport from between layers occurs due to advection – diffusion reaction. Advection occurs due to the infiltrating water and diffusion due to the potential solute gradient between top layer, middle layer and bottom layer. Figure 2.5 and 2.6 shows the accumulated total dissolved solids (TDS) in the root zone for pecan and cotton at different concentration of saline water.

As expected, the model has successfully predicted highest solute concentration in root zone for both crops irrigated with 100% groundwater. This shows that if the crops are irrigated with river water with less salt content, it will have less solute accumulated in their root zone less than 2 mg/cm$_3$ or 2000 mg/l that is less than the threshold value of pecan and cotton. This shows that with

proper treated water, the solute concentration in the root zone can be considerably reduced to favor the growth of crop without salinity stress.
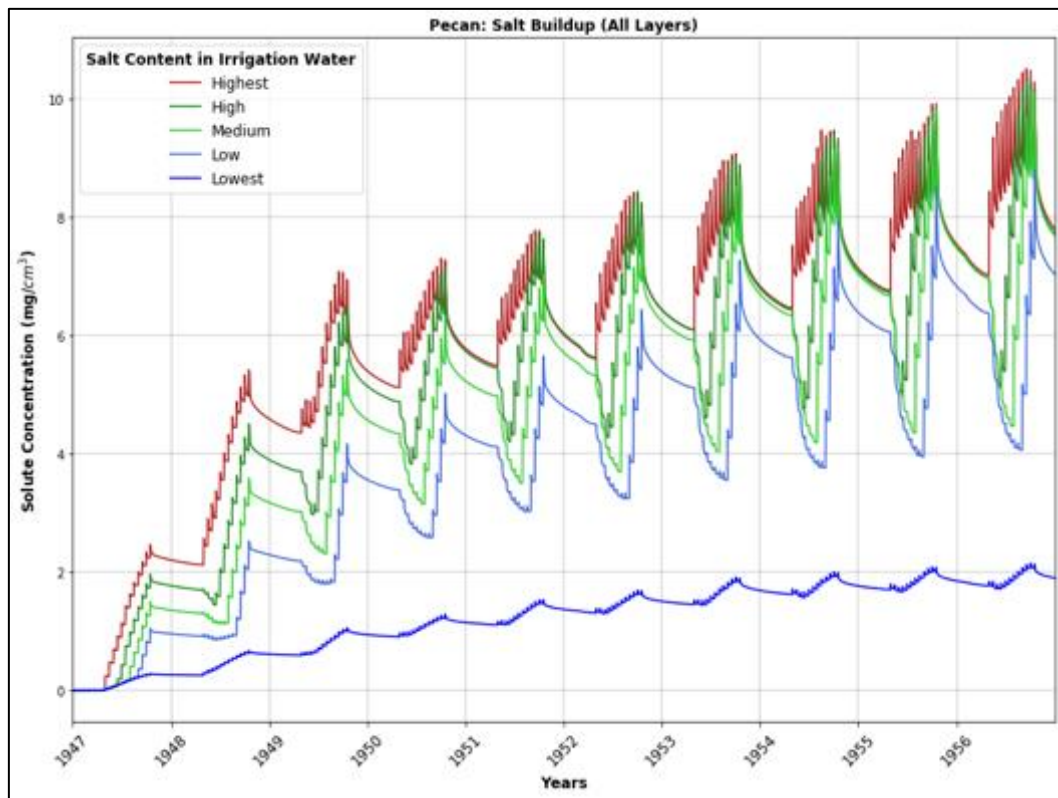
Figure 2. 5 – Salt accumulation in root zone of Pecan (1947 – 1956)
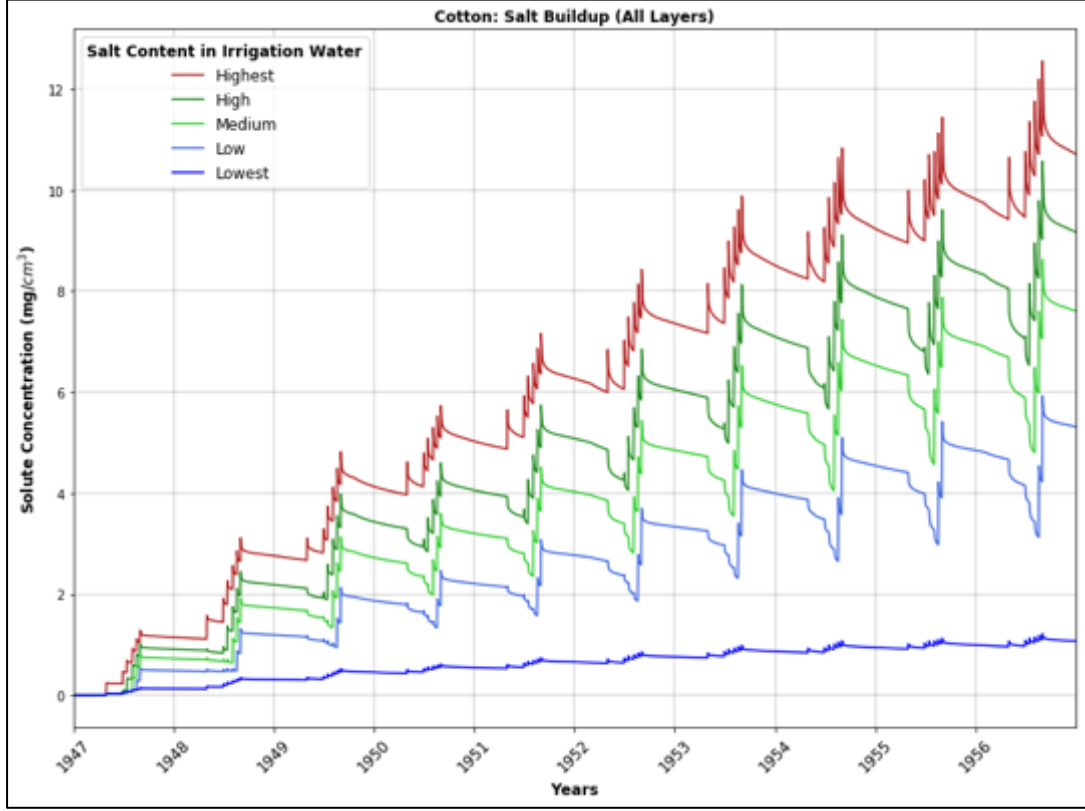
Figure 2. 6 – Salt accumulation in root zone of Cotton (1947 – 1956)

5.2   *Salinity Stress Response function (αs)*

$α_s$ is a rated value between 0 and 1 to account for the salinity stress in crops due to the accumulated solute in the root zone. A value closer to 1 suggests less stress and closer to 0 is high stress. $α_s$ is calculated using (Oster et al., 2012; van Genuchten, 1980):

$$\alpha(s) \;=\; \frac{1}{1 + \left(\dfrac{EC}{EC_{50}}\right)^3} \qquad\qquad 3$$

where, EC_{50} is the threshold value of crop and EC is the solute concentration in the root zone converted by the model using (Wallender & Tanji, 2011):

$$640 \cdot EC \ (ds/m) \;=\; TDS \ (mg/l) \qquad\qquad 4$$

Figure 2.7 and 2.8 shows that $α_s$ for pecan varies from 0.2 to 1 and cotton from 0.65 to 1 from 1947 to 1956 for different irrigation water, respectively.

57
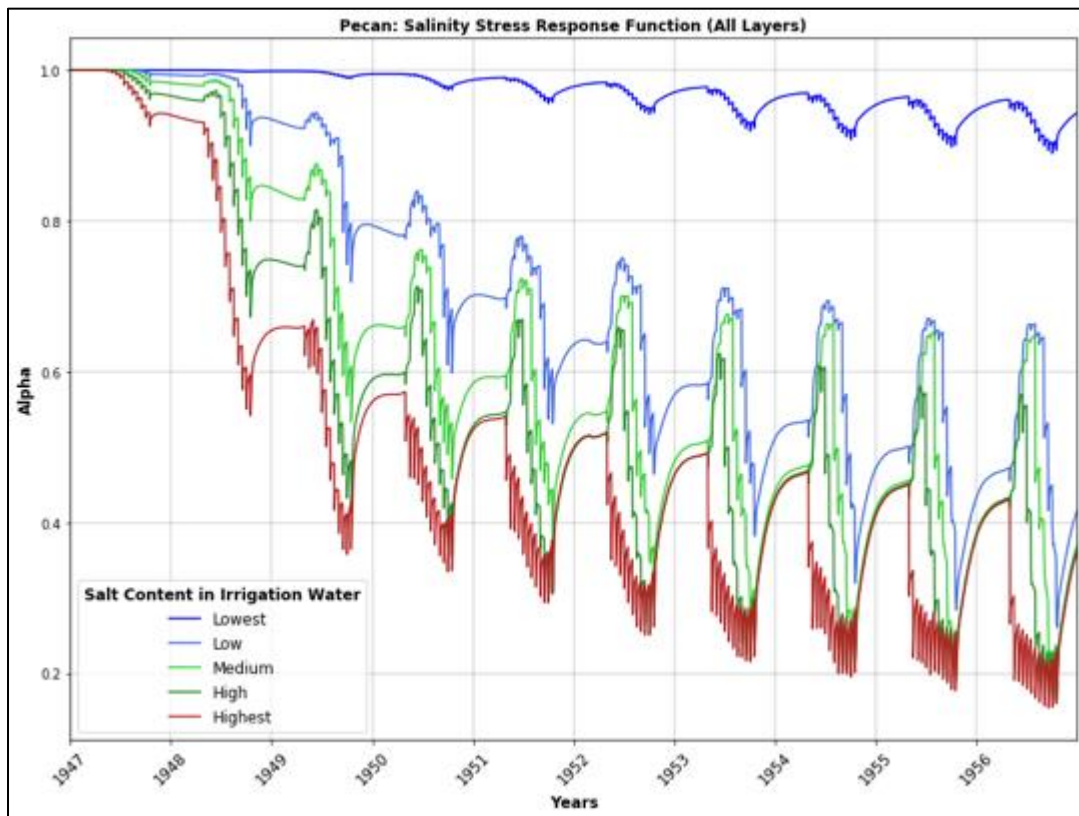
Figure 2. 7 – Salinity stress response function of Pecan (1947 – 1956)
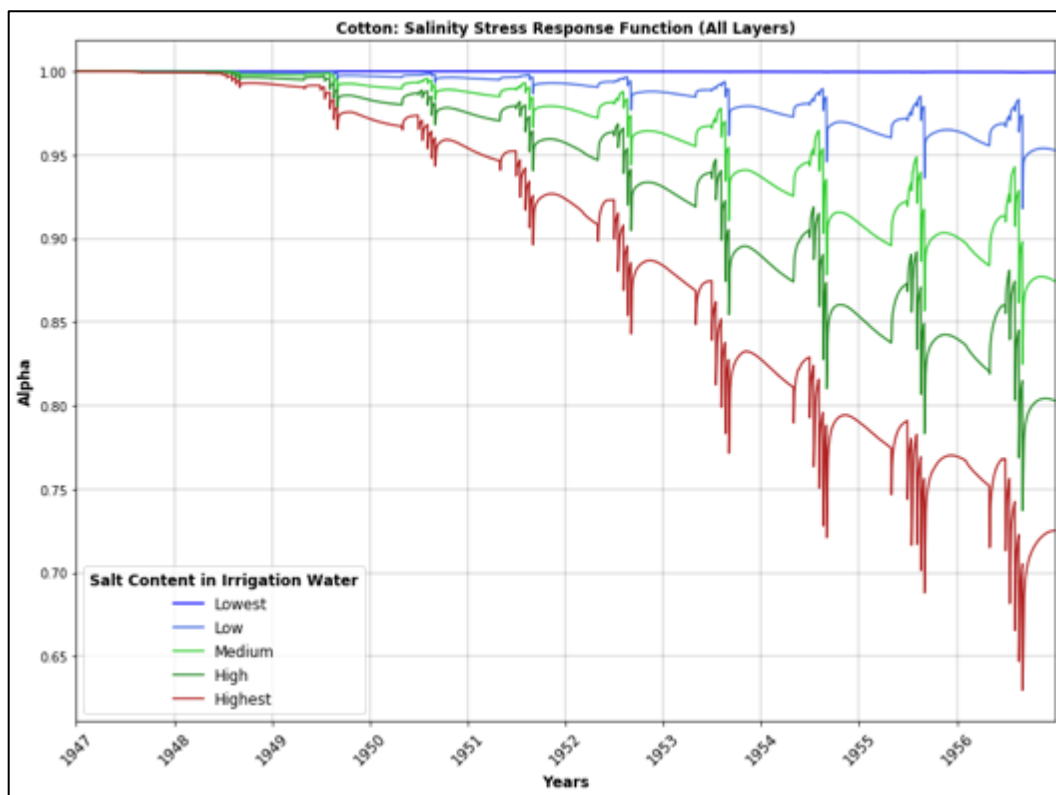
Figure 2. 8 – Salinity stress response function of Cotton (1947 – 1956)

The high variation in pecan is due to the low salt tolerance of the crop whereas cotton being highly salt tolerant shows less variation. Also, irrigation water with higher salt content (100% groundwater and 0% irrigation water) has the lowest α_s value showing that accumulated salts increases salinity stress on the crops. These salinity stresses directly affect the root water uptake of cotton and pecan.

5.3   Root Water Uptake

The increased accumulation of salt in the root zone brings α_s closer to 0 indicating high stress that reduces the actual root water uptake capacity of the crops. A comparison of the root water uptake at different concentration of irrigation water in Figure 2.9 and 2.10 shows that crops have extracted more water when irrigation water with lowest salt content was used. Cotton has less variation in the total water extracted due to its high salt tolerance.
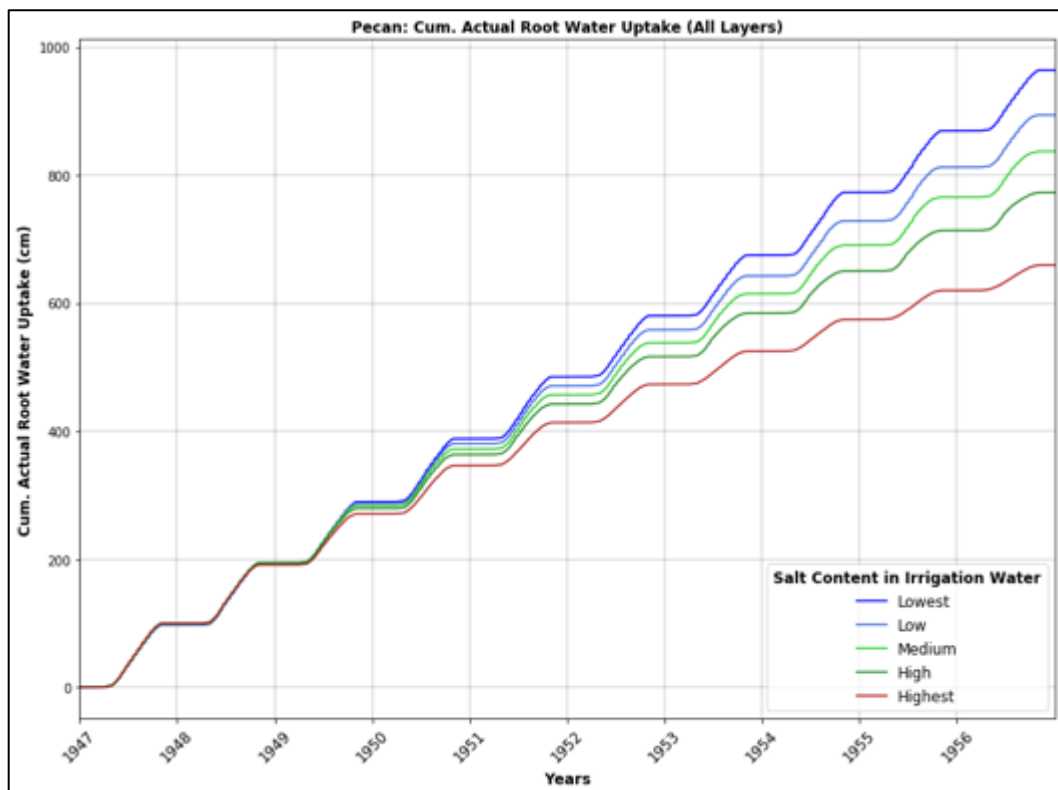
Figure 2. 9 – Root Water uptake of Pecan for varying salt content (1947 – 1956)
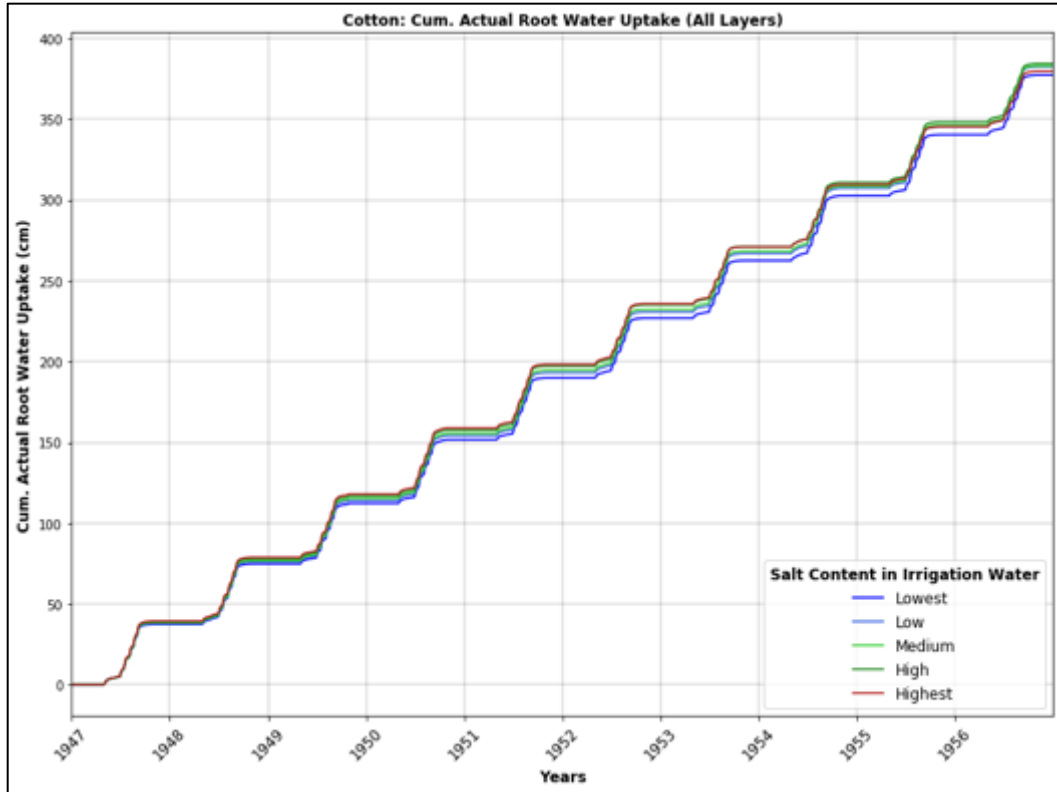
Figure 2. 10 – Root Water uptake of Cotton for varying salt content (1947 – 1956)

5.4 Data Analysis

To better understand the trend in cumulative salt accumulation (mg/cm$_3$) (Solute) and root water (cm) (RWU) for all layers, a comparison of dataset for different water was conducted. The calculated mean value for every 2 years is quantified in Table 2.8.

Table 2. 8 – Mean values at every 2 years from 1947 to 1956

Simulation	P1	P2	P3	P4	P5	C1	C2	C3	C4	C5
1947 - 1949										
Solute	2.27	1.65	1.20	0.81	0..28	1.24	0.91	0.69	0.46	0.14
RWU	91.96	92.09	91.77	90.31	90.81	36.31	35.84	35.31	34.97	34.47
1949 – 1951										
Solute	5.52	4.81	3.98	2.98	0.90	4.00	3.12	2.42	1.65	0.44
RWU	265.4	274.4	278.4	281.7	283.7	114.9	113.8	112.2	111.2	109.4
1951 - 1953										

Simulation	P1	P2	P3	P4	P5	C1	C2	C3	C4	C5
Solute	6.43	5.97	5.28	4.27	1.34	6.21	4.82	3.75	2.55	0.65
RWU	407.9	437.7	451.8	465.1	478.3	194.7	193.6	191.1	189.6	186.6
1953 – 1955										
Solute	7.29	6.75	6.22	5.22	1.66	8.44	6.76	5.39	3.69	0.86
RWU	521.5	581.5	611.2	638.2	669.1	268.8	269.0	266.2	264.7	260.5
1955 - 1957										
Solute	8.03	7.37	6.89	5.94	1.84	9.92	8.11	6.60	4.55	1.00
RWU	615.9	710.7	761.9	807.5	862.4	342.2	345.0	343.0	342.0	337.2

The data analyzes shows that the salt accumulation in the root zone for water 1, having the highest salt content, is the highest ranging from 2.27 to 8.03 mg/cm3 for pecan and 1.24 to 9.92 mg/cm3 for cotton. It can be seen that for water 5 having the least salt content, the salt accumulation is very low ranging from 0.28 to 1.84 mg/cm3 for pecan and 0.14 to 1.00 mg/cm3 for cotton.

In pecan, during the initial 2 years from 1947 to 1949, the reduction in root water uptake is not profound since the salt buildup in each layer has not reached its threshold value of 3 dS/m. Whereas, from year 1951 to 1956, pecan demonstrate considerable reduction in root water uptake with maximum difference of 246.5 cm in year 1956 between Water 5 and Water 1. This shows that the salt concentration in each layer has increased considerably enough to surpass its threshold value increasing the salinity stress.

In the initial 4 years from 1947 to 1951, cotton has hardly any reduction in the root water uptake even though salt concentration in the root zone has reached a value of 4 mg/cm3. This is attributable to its high salt tolerance with a threshold value of 7.7 dS/m. From 1951 to 1956, the accumulated salt has reached a value of 9.7 mg/cm3 and exceeded its threshold value showing a

reduction in root water uptake between water 5 and water 1 with maximum reduction of 5 cm observed in the last year 1956. This shows that cotton is highly salt tolerant and can withstand the high salt content in the arid region.

Further, Table 2.9 shows the calculated water balance for the soil column for initial and final 2 years of simulation using:

$$Water\ Applied\ =\ Root\ water\ uptake + Leached\ Water + Soil\ Water\ Storage \qquad 5$$

Table 2. 9 – Water balance with water depth in cm

Simulation	P1	P2	P3	P4	P5	C1	C2	C3	C4	C5
1947 – 1949										
RWU	191	194	195	195	194	78.8	77.9	76.8	76	74.8
Percolated	62.9	55.8	52.9	50.6	47.8	62.5	61.8	61.2	60.9	60.2
Soil Water	83.1	87.2	89.1	91.4	95.2	196	197.3	199	200.1	202
Water Applied	337	337	337	337	337	337	337	337	337	337
1955 - 1957										
RWU	84	123	147	166	191	70	73	74	75	74
Percolated	175	129	98	73	38	60	54	51	49	47
Soil Water	76.6	83.6	90.6	96.6	106.6	206	208.6	210.6	211.6	214.6
Water Applied	336	336	336	336	336	336	336	336	336	336

In the water balance, an evident trend can be seen for root water uptake that P1 with a highest salt content has a drastic reduction in root water uptake from 191 cm to 84 cm; and leached water increased from 63 cm to 175 cm between initial and final 2 years. Similar trends can be seen for P2, P3, P4 and P5 where the difference between initial and final 2 years' root water uptake decreases for each successive simulation. Such a drastic decrease in root water uptake is due to the increasing salt accumulation in the soil in 10 years. Also, irrigation water with less content of salt has less reduction in the range of 4 cm between 1947 and 1956. Whereas cotton has a less reduction

in root water uptake with a maximum reduction of 9 cm for P1 due to its high salt tolerance threshold value.

A commonly assumed relationship to calculate the ratio of reduction in crop yield due to root water uptake for pecan and cotton is given by (Skaggs et al., 2006):

$$\frac{Y}{Y_p} = \frac{T_a}{T_p}$$

6

where, Y is the yield under stress; Y_p is the yield under most favorable condition; T_a is the actual root water uptake under stress; and T_p is the actual root water uptake under most favorable condition. In this study, the most favorable condition is the simulation results from 1947 to 1949 due to the less salt buildup in the initial stage; and under stress is the simulation results from 1955 to 1957 due to the cumulative salt buildup in the final stage. The calculated percentage reduction in crop yield in the last two years compared to initial two years are shown in Figure 2.11.
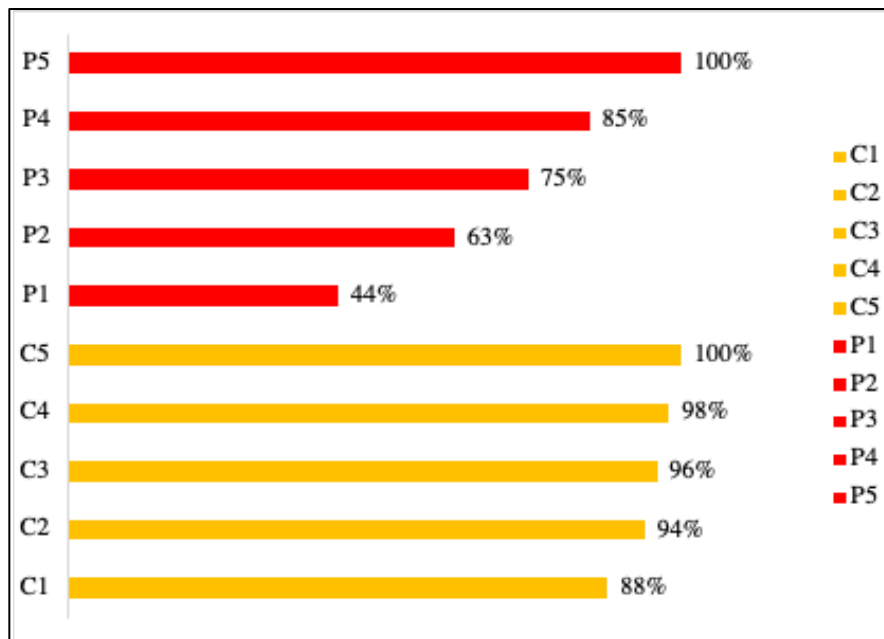
Figure 2. 11 – Percentage reduction in crop yield in cotton and pecan

It is clearly observed that pecan with highest salt content has a crop yield reduction of 44% in its crop yield in comparison to the first two years. Whereas, cotton has comparatively less crop yield reduction of 88% due to its high salt tolerance.

6.0 Conclusion

A system dynamic model was simulated for a period of drought in El Paso County, Texas from 1947 to 1956 to predict the salt accumulation in the root zone and evaluate the effect of salt stress on root water uptake of pecan and cotton. The simulation predicted the salt accumulation in the root zone for waters having five different salt concentration based on the source of water – river water (low salt) and groundwater (high salt). The prediction showed that higher the groundwater as a source of irrigation higher the salt buildup in the root zone. When 100% river water was used for simulation, the model predicted a low salt buildup ranging from 0 to 1.4 mg/cm$_3$. However, irrigation using only river water is not practical in arid region such as El Paso having very low rainfall. Therefore, proper desalination of groundwater to attain a salinity level of river water can substantially reduce the salt buildup in root zone from a range of 10 to 2 mg/cm$_3$.

Simulation results for 10 years for irrigation with water having high salt concentration showed that the root water uptake can reduce drastically resulting in a crop yield reduction of 44% for pecan and 88% for cotton. A longer regime of same irrigation water or an even higher salt concentration in irrigation water can result the crops reach its wilting point. Therefore, these simulations can be used to understand the stress tolerance of crops for different conditions and plan strategic desalination methods to prevent the crop reaching its wilting point.

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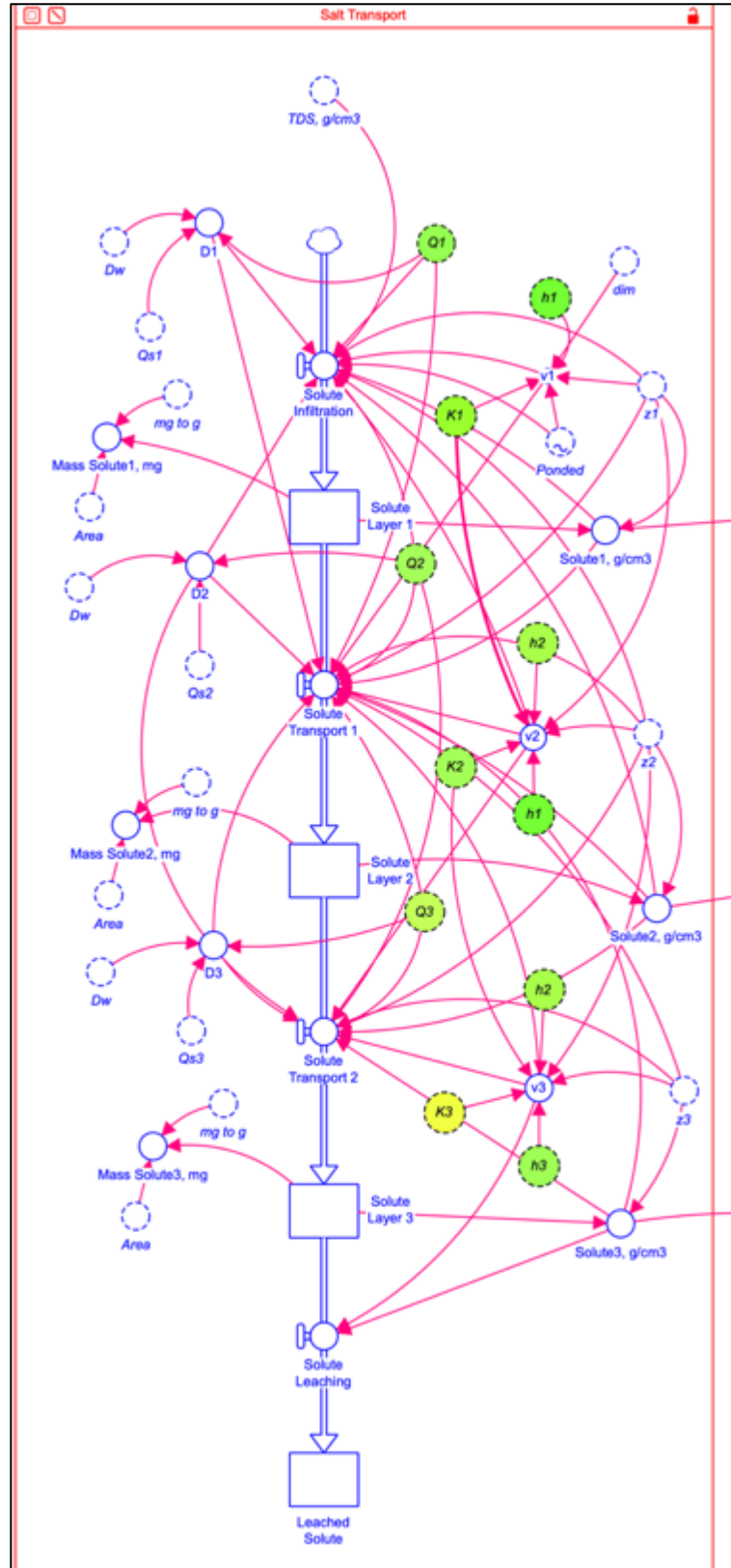
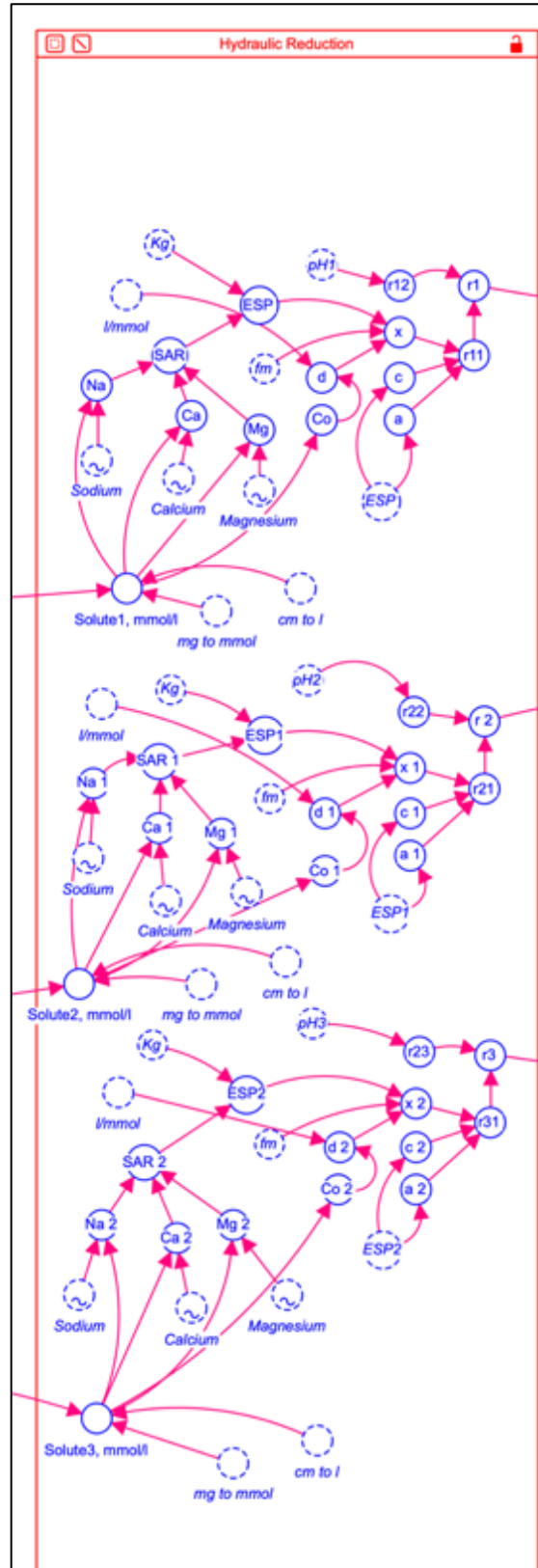**Appendix A1 – Soil Water Flow (SWF) Sector**
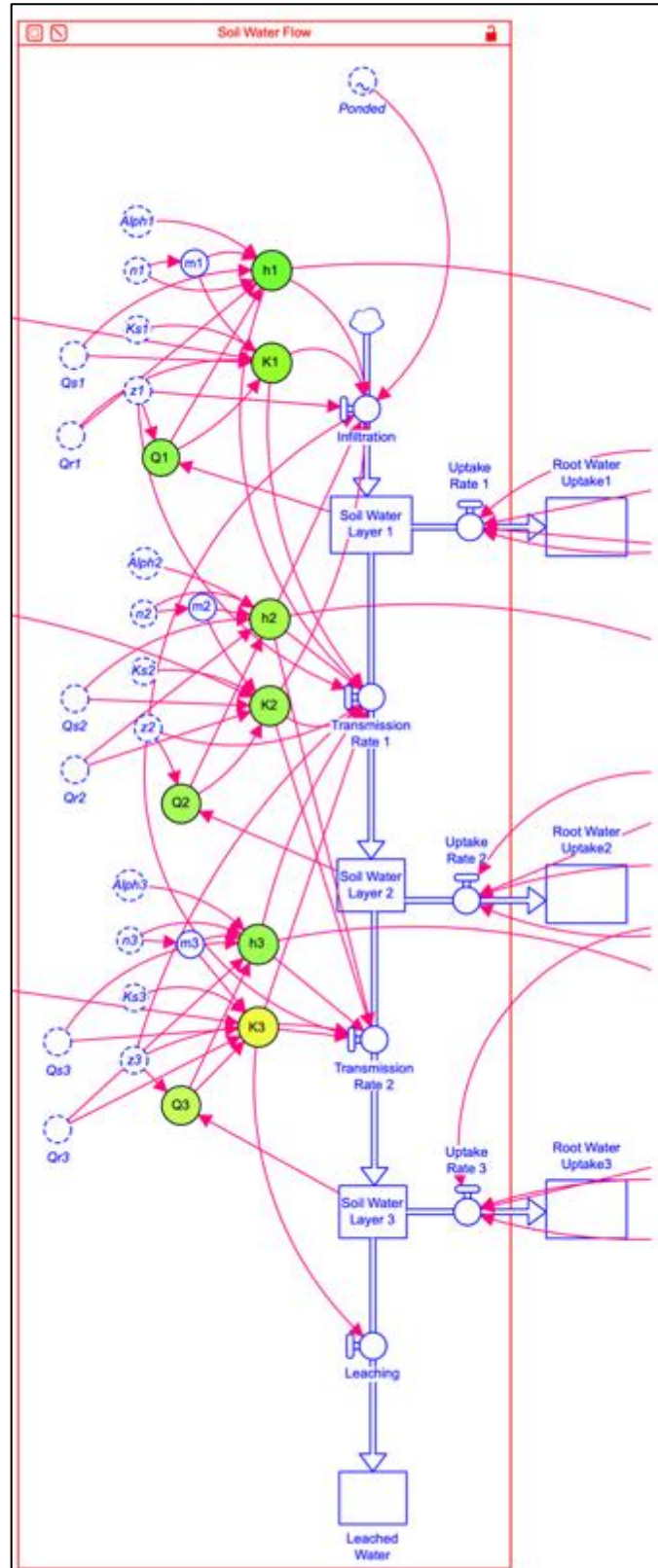
Appendix A2 – Root Water Uptake (RWU) Sector
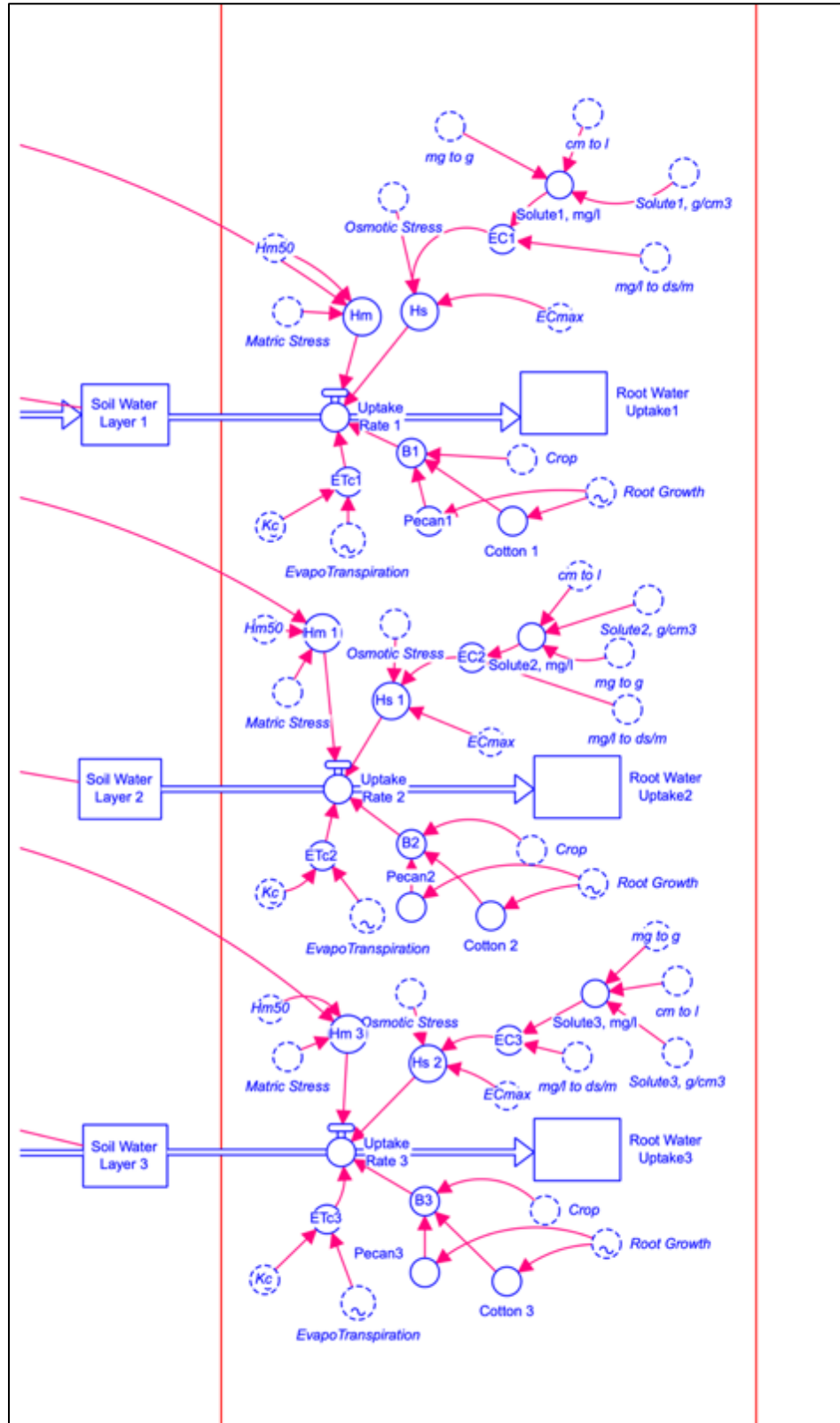
Appendix A3 – Solute Transport (ST) Sector

Appendix A4 – Hydraulic Reduction (HR) Sector

Appendix A5 – Major stock (S), converters (C) and flow (F) variables used in Model

Variable	Type	Definition	Unit
a_i	C	Soil swelling parameters	Dimensionless
$Alph\_i$	C	Van Genutchen parameter for fitting soil water retention curve (SWRC)	cm-1
Bi	C	Normalized root distribution function	Dimensionless
c_i	C	Soil swelling parameters	Dimensionless
Ca	C	Total analytical concentration of calcium	mmol/l
$Calcium$	C	Percentage of calcium	Dimensionless
Co_i	C	Total salt concentration	mmol/L
d_i	C	Soil interlayer spacing	Dimensionless
Di	C	Diffusion Constant	cm2/day
Dw	C	Diffusion constant of water	cm2/day
$EC50$	C	Crop salt tolerance threshold value	dS/m
ECi	C	Salt content at each layer	dS/m
ESP_i	C	Exchangeable Sodium Percentage	Dimensionless
$ETci$	C	Potential Evapotranspiration	cm/day
$EvapoTranspiration$	C	Reference Evapotranspiration	cm/day
fm	C	Weight fraction of montmorillonite	Dimensionless
h_i	C	Water pressure head	cm
$Hm50$	C	Water stress at 50% water extraction (h_{50})	cm
Hmi	C	Matric stress response function	Dimensionless
Hsi	C	Osmotic stress response function	Dimensionless
$Infiltration/$ $Transmission\ rate\ i$	F	Flow equations	cm per day
K_i	C	Hydraulic conductivity	cm/day

Variable	Type	Definition	Unit
Kc	C	Consumptive water use	Dimensionless
Kg	C	Modified Gapon selectivity coefficient	$(mmol\ l)_{-1/2}$
Ks i	C	Saturated Hydraulic Conductivity	cm/day
Leached Water	S	Percolated water	cm
Leaching	F	Leaching rate	cm per day
m i	C	Van Genutchen parameter for fitting SWRC	Dimensionless
Magnesium	C	Percentage of magnesium	Dimensionless
Mass Leached Solute	C	Amount of solute leached out	mg
Mass Solutei	C	Mass of Solute	mg
Mg	C	Total analytical concentration of magnesium	mmol/l
n i	C	Van Genutchen parameter for fitting SWRC	Dimensionless
Na	C	Total analytical concentration of sodium	mmol/l
pH_i	C	pH of soil	Dimensionless
Ponded	C	Ponded Water head	cm
Q i	C	Water content	$cm_3\ cm_{-3}$
Qr_i	C	Residual Water content	$cm_3\ cm_{-3}$
Qs i	C	Saturated Water content or porosity	$cm_3\ cm_{-3}$
r i	C	Hydraulic reduction function	Dimensionless
r i1	C	Hydraulic reduction due to salinity	Dimensionless
r i2	C	Hydraulic reduction due to pH	Dimensionless
Root Growth	C	Root Length	cm
Root Wateri	S	Root Water Storage	cm
SAR i	C	Sodium absorption ratio	$(mmol\ l)_{1/2}$

Variable	Type	Definition	Unit
Sodium	C	Percentage of sodium	Dimensionless
Soil_Water_Layer_i	S	Soil water storage	cm
Solute Infiltration/ Transport_i	F	Downward solute flux	g/cm^2
Solute Layer_i	S	Accumulated solute flux	g/cm^2
Solute Leaching	F	Rate of solute leached out	g/cm^2
Solutei	C	Solute concentration at ith soil	g/cm^3
Solutei, mg/l	C	Total salt concentration	mg/l
Solutei, mmol/l	C	Salt concentration from ST sector	mmol/l
TDS, g/cm3	C	Initial solute concentration	g/cm^3
Uptake Ratei	F	Rate of water extraction	cm per day
x_i	C	Swelling factor of soil	Dimensionless
z_i	C	Soil layer depth	cm

Vita

Thomas Poulose completed his bachelor's degree in Civil Engineering from India in 2012. He joined the civil engineering industry under a Government of India owned company in Delhi, India and worked under various roles from 2012 to 2018. He was deputed to Rwanda, Africa under a Government of India line of credit (LoC) project in year 2014 as Project Manager. In Rwanda, he managed a multimillion US dollar Irrigation Project and was the key person to the Ministry of Agriculture and Animal Resources, Republic of Rwanda. After completion of his mission in 2018, he embarked to United States for higher studies in water and environment at University of Texas at El Paso (UTEP). During his graduate studies, he had successfully secured an internship with Michael Baker International for hydrological and hydraulic modelling. At UTEP, he has been involved in the United States Department of Agriculture funded project to develop a system dynamic model to assess the salinity and water stress of crops in El Paso county, Texas. He has developed three papers related to research topics covering energy conservation, salinity and water infiltration. His interests lie in modeling of hydrological and hydraulics process; and infiltration processes with special emphasis on salinity.

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