Riparian Habitat Establishment Model

RHEM

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Riparian Habitat Establishment Model (RHEM)

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Note to Reader

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5. RHEM

The Riparian Habitat Establishment Model (RHEM) simulates unsaturated ground water flow and detailed bioenergetics of individual cottonwood. The Mid-Pacific Region of the Bureau of Reclamation (Reclamation) and the Stockholm Environment Institute (SEI) developed this model. It is a modified version of the variably saturated flow code HYDRUS 2-D[1] (Simunek et al., 1999). The model simulates individual cottonwood seedling growth, while incorporating the effects of sediment gradation and hydraulic properties, water table depth, and atmospheric conditions. This chapter describes:

- *Controlled seedling growth experiments used to determine the parameters for RHEM algorithms*
- *Model calibration and validation*
- *Application of the model to develop the parameters for the Sedimentation and River Hydraulics One-Dimensional Sediment Transport and Vegetation Dynamics Model (SRH-1DV)*

5.1 Controlled Seedling Growth Experiments

Controlled experiments were conducted to determine the numerous cottonwood seedling growth parameters for RHEM, including growth rate, root-shoot allocation, and water stress thresholds.

5.1.1 Experiment Design

A system of 30 rhizopods[2] was constructed on the University of California at Davis campus. Each rhizopod consisted of a 45-centimeter (cm) diameter polyvinyl chloride (PVC) tube, open on one end, 154 cm long, and filled with a medium to coarse sand with a similar gradation to that found along the Sacramento River on the downstream portion of the point bar at river mile (RM) 192.5 (tables 5-1 and 5-2). Additional tubes were installed in each rhizopod for controlling the water table, observing soil moisture, and extracting intact seedlings. The rhizopods were placed in a pre-existing, rectangular, concrete lined pit. A wooden cover over the pit, which had cutouts for each rhizopod, minimized the exposure of the rhizopod sides to solar radiation (figure 5-1).

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[1] HYDRUS 2-D is a software package for simulating water, heat, and solute movement in two- and three-dimensional variably saturated media. See: http://www.pc-progress.com/en/Default.aspx?hydrus-3d

[2] An apparatus constructed to grow tree seedlings under a precise rate of reduction in water table elevation.

Table 5-1. Grain Size Analysis for Sand Used in Controlled Experiments

Sieve Size (mm)	% Mass Retained
4	0.04
2	12.76
1	20.84
0.5	25.33
0.25	27.84
0.13	10.40
0.063	2.17
<0.063	0.62

Note: mm = millimeters

Table 5-2. Soil Physical Properties and Fitted van Genuchten Parameters (van Genuchten 1980) for Sand Used in Controlled Experiments

Parameter	Value
Bulk density	1.81 grams/cm^3
Saturated water content	27.7%
Saturated hydraulic conductivity	5.21×10^{-3} cm/d
α	0.04 cm^{-1}
n	3.84
θ_r	5.5%

Note: cm^3 = cubic centimeters, cm/d = centimeters per day

The experiment consisted of five treatments: T1, T2, T3, T4, and T5. Each treatment had 5 replicates, and each treatment had an "evaporation" rhizopod in which no seedlings were planted (5 treatments x 5 replicates + 5 evaporation = 30 rhizopods). These rhizopods were used to measure the rate of bare soil evaporation.

At the beginning of the experiment, the water table was maintained at 5 cm below the soil surface, and cottonwood seeds collected from the Sacramento River were sown. Treatments began 10 days after germination (June 28, 2008) and continued until the end of the experiment. Each treatment subjected the cottonwood seedlings to a different level of water stress. In treatments T1 – T4, the water table was lowered at a rate of 1, 2, 3, and 4 cm/d, respectively. In treatment T5, the seedlings were irrigated twice a day, and the rhizopod was allowed to freely drain.

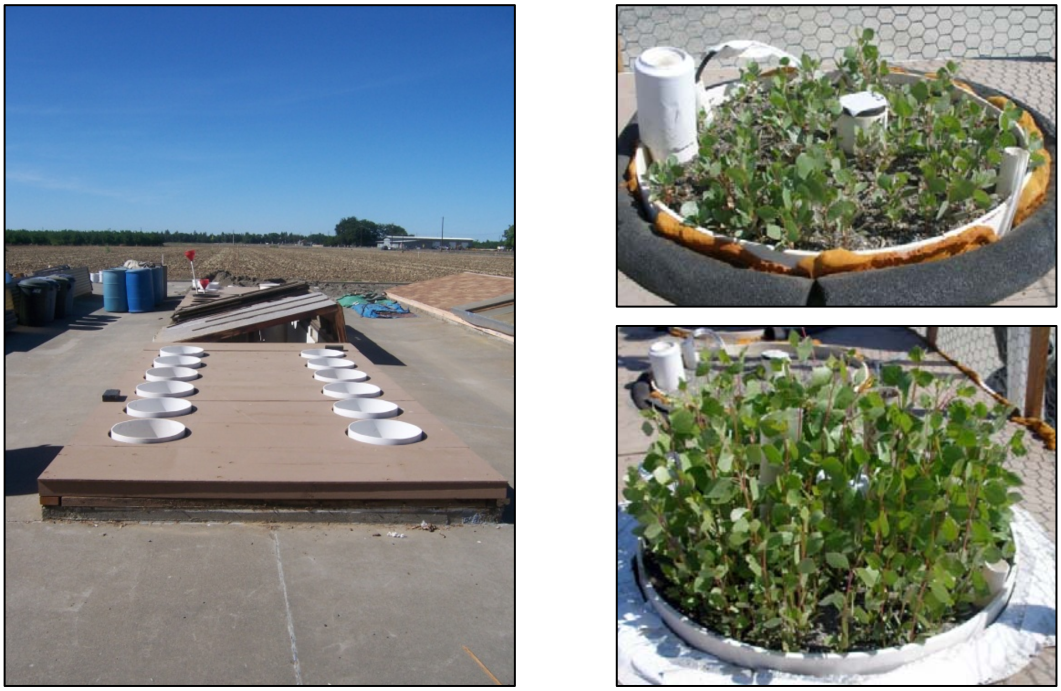

Figure 5-1 - Rhizopod Experiment Setup and Cottonwood Seedlings

In Figure 5-1, the photograph on the left shows the tops of 12 rhizopods located on the southern end of the rhizopod system. An additional 18 rhizopods are located on the north side of the entryway. The photograph on the right shows seedlings in the T1 (top) and T5 (bottom) treatments after 62 days of growth.

Each harvest consisted of the extraction of three individual plants from each rhizopod. After each harvest, plant samples were processed to measure total dry biomass, shoot biomass, root biomass, leaf area, maximum root depth, and root distribution in 10-cm-deep increments. The initial harvest (H1) took place on June 27, 9 days after germination (June 18, 2008).

Treatments T1, T2, and T3 were continued for a total of 40 days, during which an additional three harvests were made of individual seedlings (H2 – H4), which occurred on July 9, July 16, and July 28. Treatment T4 had complete plant death by 27 days after germination. Treatment T3 had complete plant death by H4, 40 days after germination. Treatments T1, T2, and T5 were still alive at H4.

5.1.2 Experiment Results and Discussion

Differences between treatments were observed in overall biomass production, root depth, and plant survival (figure 5-2 and tables 5-3 and 5-4). Plants in all treatments grew at nearly the same rate through H2; however, by H3, the plants in T5 had grown larger than the others, and the plants in T4 were smaller. By H4, the plants in T5 had more biomass than plants in T1 and T2: 60 percent and 40 percent, respectively. The T4 plants had died, and the last surviving T3 plants had a biomass that was only 50 percent of the T1 plants' biomass.

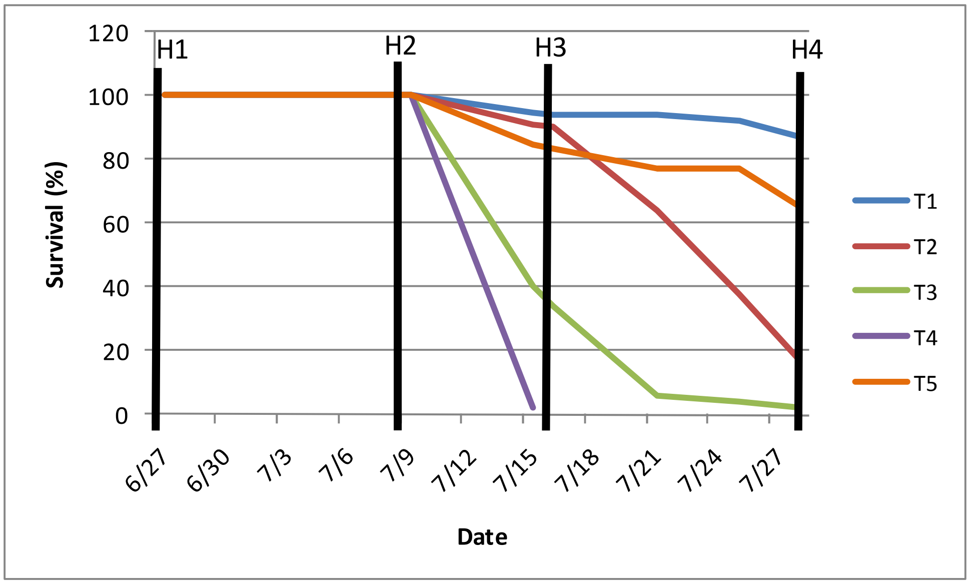

Figure 5-2. Seedling survival during controlled water table decline experiments. T1 = 1 cm/d, T2 = 2 cm/d, T3 = 3 cm/d, T4 = 4 cm/d, and T5 was irrigated twice daily and allowed to freely drain. Germination was June 18 and the 40th day (H4) is July 28.

Table 5-3. Total Average Per-Plant Biomass (mg)

Harvest/Date	T1	T2	T3	T4	T5
Germination/June 18					
H1/June 27	2.64	3.14	2.28	2.59	2.51
H2/July 9	10.66	12.06	9.23	13.04	12.00
H3/July 16	22.84	25.02	22.52	10.70	36.86
H4/July 28	31.51	36.22	16.54	[1]	52.31

Note: mg = milligrams
[1] By H4, the T4 plants had died.

Table 5-4. Total Average Maximum Root Depth (cm)

Harvest/Date	T1	T2	T3	T4	T5
H1/June 27	9.00	8.50	7.50	7.50	7.50
H2/July 9	17.00	21.00	16.00	26.67	19.00
H3/July 16	38.00	44.00	34.00	20.00	38.00
H4/July 28	44.29	59.09	40.00	[1]	43.13

[1] By H4, the T4 plants had died.

The different total biomass values observed between treatments are explained by a combination of water logging and drought stress. In the beginning of the experiment, the sediments were equally saturated in all treatments, and the similar biomass values recorded for H1 reflect this. Treatments were started 2 days after H1. By H2, there was still little difference between the treatments in terms of average plant biomass. However, the root depth was greatest for T4, as those plants attempted to grow into the moist sediment above the rapidly declining water table. By H3, the plants in T5 were clearly growing at the most rapid rate. This was due to the combination of good root aeration caused by draining the T5 rhizopods and an ample supply of water from the twice-daily irrigations. In contrast, the T1 and T2 plants had access to ample water but were experiencing waterlogging stress caused by the relatively slow water table decline rates. Plants in T3 and T4 were stressed by a lack of water, and no T4 plants survived beyond H3. By H4, the plants in T5 were continuing their relatively rapid growth. Plants in T3 were severely stressed by lack of water and almost completely dead. The plants in T2, while having produced more biomass than T1 plants, were suffering from drought stress by H4, and survival was rapidly declining (figure 5-2). Results of the study illustrate the extreme sensitivity of cottonwoods to water table decline, and the impacts of both desiccation and inundation on biomass and survival. Natural cottonwood survival is limited by soil moisture retention, the rate of water table decline, and potential precipitation.

5.2 Model Algorithms

To develop a computer model capable of simulating seedling growth, stress, and death, a set of algorithms was developed based on relationships defined in the literature and observations made during the experiment described above. Plant growth in RHEM is represented by a series of equations used to simulate dry matter or biomass production, the partitioning of growth between above ground biomass, or canopy, and below ground root biomass, and the depth distribution of roots. Equations for potential and actual transpiration are used to estimate seedling water stress. Due to the importance of root zone water availability for the survival of cottonwood seedlings, particular attention was devoted to the distribution of root growth within the root zone. Initial conceptualization of this model was derived from Adiku et al. (1996). The model assumes that potential stressors such as nutrients, heat, and shading are not a factor. Only stresses caused by an excess or lack of water are considered.

5.2.1 Plant Growth

The first step in computing seedling growth is the calculation of potential growth assuming no water stress (Neitsch et al. 2005), as shown in equation 5-1:

$$\frac{d(Wg_{\max}(t))}{dt} = eS(1-e^{-kL}) \qquad 5\text{-}1$$

Where:

$Wg_{max}(t)$ = the dry matter per unit area under ideal conditions in kilograms per square meter (kg m^{-2})

e = the radiation use efficiency in kilograms per mega-joule (kg MJ^{-1})

S = the incident radiation in mega-joules per square meter per second (MJ m^{-2} s^{-1})

k = the light extinction coefficient in meters per square meters (m m^{-2})

L = the leaf area in square meters (m^2)

The radiation use efficiency is reduced under high vapor pressure deficit conditions using the relationship (Neitsch et al. 2005) shown in equation 5-2:

$$e = \begin{cases} e_{vpd=1} - \Delta e_{dcl}\,(vpd - vpd_{thr}), vpd > vpd_{thr} \\ e_{vpd=1},\ vpd \le vpd_{thr} \end{cases} \qquad 5\text{-}2$$

Where:

$e_{vpd=1}$ = the radiation use efficiency when the vapor pressure deficit is 1 kilopascal (kPa)

Δe_{dcl} = the rate of decline in the radiation use efficiency per unit decrease in the vapor pressure deficit in kilograms per mega-joule per kilopascal (kg MJ^{-1} kPa^{-1})

vpd = the vapor pressure deficit (kPa)

vpd_{thr} = the threshold vapor pressure deficit above which the plant will have a reduced radiation use efficiency (kPa)

The actual growth rate is calculated as the potential growth rate limited by a factor that is a function of the degree of water stress, as shown in equation 5-3:

$$\frac{d(Wg_a(t))}{dt} = f_g \frac{d(Wg_{max}(t))}{dt} \qquad 5\text{-}3$$

Where:

$Wg_a(t)$ = the actual dry matter per unit area (kg m^{-2})

f_g = a growth reduction function based on the ratio of actual transpiration (T_a) to potential transpiration (T_p) where T_r is the threshold value of T_a/T_p. This ratio serves as a sign of drought stress, since T_a is reduced relative to T_p as soil moisture conditions become limiting.

For T_a/T_p values less than 1.0, growth is limited as shown in equation 5-4.

$$f_g = \begin{cases} 1.0, & \frac{T_a}{T_p} = 1.0 \\ T_a/T_p, & \frac{T_a}{T_p} < 1.0 \end{cases} \qquad \text{5-4}$$

Once actual biomass production is calculated, biomass is partitioned to either the shoot or root system. Greenhouse observations have shown that cottonwood seedlings divert more energy to root growth when soil moisture conditions are limiting (Kranjcec et al. 1998). In this model, dry matter growth is partitioned between roots and shoots as a function of the ratio T_a/T_p as shown in equation 5-5a (shoots) and 5-5b (roots).

$$\frac{d(Ws_a(t))}{dt} = (1 - RMRatio)\frac{d(Wg_a(t))}{dt} \qquad \text{5-5a (shoots)}$$

$$\frac{d(Wr_a(t))}{dt} = [RMRatio]\frac{d(Wg_a(t))}{dt} \qquad \text{5-5b (roots)}$$

Where:

$Ws_a(t)$ = the actual shoot dry matter (kg m^{-2})

$Wr_a(t)$ = the actual root dry matter (kg m^{-2})

The root-mass-ratio (RMRatio) is a partitioning factor and a function of T_a/T_p as calculated in equation 5-6.

$$RMRRATIO = \begin{cases} RMR_{max}, & \frac{T_a}{T_p} < T_{mrc} \\ RMR_{max} - \frac{\frac{T_a}{T_p} - T_{mrc}}{T_{src} - T_{mrc}} \left(RMR_{max} - RMR_{min} \right) & , T_{mrc} \le \frac{T_a}{T_p} \le Tsrc \\ RMR_{min}, & \frac{T_a}{T_p} > T_{src} \end{cases} \quad \text{5-6}$$

Where:

T_{src}, T_{mrc} = threshold values for defining the minimum and maximum RMRatios.

At T_a/T_p values greater than the threshold T_{src}, the RMRatio is equal to a minimum value, RMR_{min}. For decreasing values of T_a/T_p less than T_{src}, plant growth is increasingly allocated to the roots until a maximum RMRatio value is reached at the threshold value of T_{mrc}. For T_a/T_p values less than T_{mrc}, the RMRatio is equal to the maximum value, RMR_{max}.

Once the shoot biomass is calculated, a relationship between shoot biomass and leaf area can be used to calculate the change in leaf area relative to plant growth, as shown in equation 5-7.

$$L(t) = f_L Ws_a(t) \quad \text{5-7}$$

Where:

L = leaf area (m^2)

f_L = a factor that converts shoot biomass to leaf area (m^2 leaf area/kg m^{-2})

5.2.2 Root Growth

Root front is the deepest point of the roots. After the simulated plant biomass is partitioned into roots and shoots, the root front is extended, the new root mass is distributed over the root zone, and the root mass is converted into root length for eventual use in the calculation of actual transpiration.

The root front velocity (how fast the root grows) of cottonwood seedlings varies according to changing soil moisture conditions (Amlin and Rood 2002). Under conditions of drought stress, seedlings will increase the root front velocity. Presumably, this is an effort by the plants to grow roots into sediment with more available water. In coarse soils (gravels and cobbles), ample supplies of soil water are only available in the zone of capillary rise[3] close to the water table. In coarse soils, this zone is relatively thin; whereas in finer grained soils (fine sand and silts), the zone is thicker. Results from the experiment described above indicate that seedlings extend the root front at a rate of 1 to 3.5 cm/d. Additionally, it was observed that roots can grow up to 15 cm below the water table. These two phenomena are captured in the root front velocity algorithm (equation 5-8):

$$\frac{d(D_r(t))}{dt} = V_r \; f_{vr}(\Psi) \qquad 5\text{-}8$$

Where:

$D_r(t)$ = the depth of the root zone (cm) at time t

V_r = the root front velocity in centimeters per hour (cm/h)

f_{vr} = a root front velocity reduction factor that is a function of the pressure head at the root front

Ψ = pressure head

The root front velocity is a function of the degree of water stress as calculated in equation 5-9.

$$V_r = \begin{cases} V_{r\max}, & \frac{T_a}{T_p} < T_2 \\ V_{r\max} - \frac{\frac{T_a}{T_p} - T_2}{T_1 - T_2}\left(V_{r\max} - V_{r\min}\right), & T_2 \le \frac{T_a}{T_p} \le T_1 \\ V_{r\min}, & \frac{T_a}{T_p} > T_1 \end{cases} \qquad 5\text{-}9$$

The root front velocity reduction factor limits root growth into sediments below the water table as calculated in equation 5-10.

$$f_{vr} = \begin{cases} 1.0, & \Psi < \mathrm{DBWT} \\ 0.0, & \Psi \ge \mathrm{DBWT} \end{cases} \qquad 5\text{-}10$$

Where:

DBWT = pressure head value (expressed as depth below the water table) above which root growth ceases (cm)

[3] The zone of capillary rise is defined as the region of the soil profile in which soil pores are completely filed by water but where the capillary pressure is less than atmospheric.

Next, the root growth is distributed within the root zone. Adiku et al. (1996) address this issue with a model that predicts root growth as a function of the overall increase in root biomass and the moisture distribution with depth, as shown in equation 5-11.

$$\frac{d(Wr_A(z,t))}{dt} = Wr_A(z,t) P_r [1 - \frac{Wr_A(z,t)}{Wr_{Am}}] E_f(S_\theta) \qquad \text{5-11}$$

Where:

$Wr_A(z,t)$ = the root mass per unit area (kg m^{-2}) at depth z and time t

Wr_{Am} = the maximum root mass of the plant (kg m^{-2})

P_r = the net root proliferation rate per second (s^{-1})

$E_f(S_\theta)$ = a function that limits root growth as a function of soil moisture where S_θ is the soil saturation.

E_f serves as a proxy for soil strength, which increases as soil moisture declines and, therefore, limits root extension as determined in equation 5-12.

$$E_f = \begin{cases} 0.0, & S_\theta < S_L \\ \frac{S_\theta - S_L}{S_c - S_L}, & S_L \le S_\theta \le S_c \\ 1.0, & S_\theta > S_c \end{cases} \qquad \text{5-12}$$

Where:

S_L and S_c = threshold values of soil saturation. Root extension ceases for soil moisture values lower than S_L and is at its maximum for values greater than S_c.

Adiku et al. (1996) present a method for solving equation 5-11 without specifying the net root proliferation rate, P_r. Using this method, the right-hand side of equation 5-11 is solved for each depth increment (assuming that P_r is constant with depth and time). These values are then divided by the sum of values for all depth increments in the root zone, thereby creating a weighting factor used to distribute the total root growth over the depth increments and allowing for cancellation of P_r, as shown in equation 5-13.

$$\Delta Wr_{A_i}^{t} = \frac{Wr_{A_i}^{t-1}[1 - \frac{Wr_{A_i}^{t-1}}{Wr_{Am}}] E_f(S_{\theta i}^{t-1})}{\sum_{j=1}^{N} Wr_{A_j}^{t-1}[1 - \frac{Wr_{A_j}^{t-1}}{Wr_{Am}}] E_f(S_{\theta j}^{t-1})} \Delta Wr_a^{\,t} \qquad \text{5-13}$$

Where:

ΔWr_{Ai}^{t} = the change in root mass per unit area at depth increment *i* during time step *t*

Wr_{Ai}^{t-1} = the root mass per unit area at depth increment *i* during the previous time step

$S_{\theta i}^{t-1}$ = the soil saturation in soil depth increment i during the previous time step

N = the total number of depth increments in the root zone for j =1, 2, 3…N.

Finally, the increase in root dry matter per unit area, ΔWr_{Ai}^{t}, is converted to root length per unit area for each depth increment in the root zone by multiplying by specific root length, c (in meters per kilogram [m kg^{-1}]), which is calculated as a function of the soil moisture conditions, as shown in equation 5-14.

$$\frac{d(R_{A,i}(t))}{dt} = c(\theta_i(t))\frac{d(Wr_{a,i}(t))}{dt} \qquad 5\text{-}14$$

Where:

$R_{A,i}(t)$ = the total root length per unit area (m m^{-2}) for root zone layer *i*

The value of specific root length, c (in m kg^{-1}), varies as a function of soil saturation in root zone layer i, as calculated in equation 5-15:

$$c = S_{\theta} * (c_{\max} - c_{\min}) + c_{\min} \qquad 5\text{-}15$$

Where:

c_{max} = the maximum value of the specific root length

c_{min} = the minimum value of the specific root length

5.2.3 Plant Transpiration

Potential transpiration by a seedling is estimated using equation 5-16, which is a modified version of the Penman-Monteith equation (Zhang et al. 1997).

$$Tp^{t} = L_A(t)\frac{sR_n + 0.93\rho_{air}C_p D / r_b}{\lambda[s + 0.93\gamma(2 + \bar{r}_s / r_b)]\rho_{H_2 0}} \qquad 5\text{-}16$$

Where:

T_p^t = the transpiration rate per unit leaf area in grams per square meter per second ($g\ m^{-2}s^{-1}$)

λ = the latent heat of vaporization of water in joules per gram ($J\ g^{-1}$)

L_A = the total leaf area of the tree canopy (m^2)

s = the slope of the saturation vapor pressure curve in kilopascals per degree centigrade ($kPa\ ^oC^{-1}$)

R_n = the net radiation absorbed per unit leaf area in watts per meter squared ($W\ m^{-2}$)

ρ_{air} = the density in kilograms per cubic meter ($kg\ m^{-3}$) of air at constant pressure

C_p = the specific heat capacity in joules per kilogram per degree Kelvin ($J\ kg^{-1}\ ^oK^{-1}$) of air at constant pressure

D = the saturation vapor pressure deficit of the air (kPa)

r_b = the leaf boundary layer resistance in seconds per meter ($s\ m^{-1}$)

γ = the psychometric constant ($kPa\ ^oC^{-1}$)

$\bar{r}_s$ = the minimum stomatal[4] resistance ($s\ m^{-1}$)

ρ_{H_20} = the density of water in grams per cubic meter ($g\ m^{-3}$)

The RHEM approach sets the stomatal resistance at a minimum value based on observations made during the experiment of unstressed plants.

Maximum transpiration limited by the root's ability to uptake water is calculated using equation 5-17:

$$T_{a_R}^t = \sum_{i=1}^{N} T_{a_{R_i}}^t = \sum_{i=1}^{N} q_r R_{A,i}^{t-1} RW(\theta_i^{t-1}) \qquad 5\text{-}17$$

Where:

$T_{a_R}^t$ = the root limited maximum transpiration rate for time step t ($m^3\ H_20\ m^2\ s^{-1}$)

[4] Note that stomata are pores in the leaf and stem epidermis used for gas exchange.

q_r = the maximum uptake of water per unit root length per unit time (m^3 H_20 m^{-1} root t^{-1})

RW = a dimensionless factor that limits transpiration as a function of soil moisture content during the previous time step

$T_{a\,Ri}^{\,t}$ = the root limited maximum transpiration for depth increment *i*.

The RW function (as calculated using equation 5-18) limits transpiration when pressure head, Ψ, is either below a threshold value, P_2, (water limiting) or above a threshold value, P_1 (water logging) (Feddes et al. 1978; Simunek et al. 1999). For values of h below the wilting point (h_{WP}), transpiration ceases.

$$RW = \begin{cases} 0.0, & \Psi < P_3 \\ \frac{\Psi - P_3}{P_2 - P_3}, & P_3 \le \Psi \le P_2 \\ 1.0, & P_2 \le \Psi \le P_1 \\ \frac{\Psi - P1}{P0 - P1}, & P_1 \le \Psi \le P_0 \\ 0.0, & \Psi > P_0 \end{cases} \qquad 5\text{-}18$$

During initial simulations using the model described in equation 5-18, it was discovered that the water logging stress parameters P_0 and P_1 limit transpiration when the water table is close to the soil surface, due to the high water content caused by the capillary rise of water from the water table. This conflicted with observations of seedlings growing and transpiring with roots in saturated sediment. It was assumed that seedlings are able to grow under these conditions due to oxygen diffusion from the atmosphere into the near surface sediments. To mimic this effect, the constraint on transpiration imposed by the P_0 and P_1 parameters was relaxed in the top 8 cm of soil. Within these soil layers, the seedlings were allowed to transpire up to 8.8 x 10^{-4} cm/h, which is based on the calculated value for potential evapotranspiration (ET) on June 29, 2008, of the controlled growth experiments. Observations made during the experiments indicate that the plants grew well during the initial 11 days of growth, and roots extended to 8 cm deep by June 29. During this period, the water table was 5 cm deep. On June 29, visual observations indicated that the plants were in distress and, for that reason, the water table decline treatments were started. In summary, based on these observations, the authors assume that oxygen diffusion into the near surface sediments allows a maximum of 8.8 x 10^{-4} cm/h of transpiration using water from the top 8 cm of sediment.

The actual transpiration is calculated by comparing the maximum transpiration that can be supported by the roots, Ta_R^t, to the potential atmospheric transpiration demand, Tp^t, for the current time step. When Ta_R^t is greater than or equal to Tp^t, the transpiration is partitioned into the root zone depth increments using equation 5-19a.

$$Ta_i = Tp^t / Ta_R^t \, (Ta_{Ri}^t) \qquad 5\text{-}19a$$

Otherwise, the transpiration in each root zone depth increment is given by equation 5-19b:

$$Ta_i = Ta_{Ri}^{\ t} \qquad 5\text{-}19b$$

5.3 Calibration

The first step in calibration was to set all parameters to values observed during the controlled experiments. These included most of the parameters in the model (table 5-5). The next step was to run the model and determine if HYDRUS 2-D[5] was solving properly. This process required adjusting the time step controls and the minimum allowable pressure head at the soil surface (hCritA), which is used to calculate the atmospheric flux boundary condition. For finer-grained soils, this value is often on the order of -10,000 cm; however, as sand was modeled in this case, using such small values resulted in numerical instability. Using recommendations found on the HYDRUS 2-D user forum, a pressure head with a water content equivalent to a small fraction of the pore space was used. The value used was -50 cm.

Table 5-5. Model Parameters Set Using Field Observations

Variable	Value	Equation	Variable	Value	Equation
$e_{vpd=1}$	0.003 kg MJ^{-1}	5-2	Δe_{dcl}	0.0008 kg MJ^{-1} kPa^{-1}	5-2
vpd_{thr}	1.0 kPa	5-2	RMR_{max}	0.57	5-6
RMR_{min}	0.41	5-6	T_{mrc}	0.5	5-6
Tsrc	0.9	5-6	f_L	0.015 m^2 leaf area/kg m^{-2}	5-7
Vr_{min}	0.075 cm/h	5-9	Vr_{max}	0.235 cm/h	5-9
DBWT	15 cm	5-10	c_{max}	300,000 m kg^{-1}	5-15
c_{min}	100,000 m kg^{-1}	5-15			

The next step of the process was to adjust parameters relating to water logging, drought stress, and root growth until simulated values matched observed values. This was done in several steps:

1. The potential growth parameters from equation 5-2, $e_{vpd=1}$, Δe_{dcl}, vpd_{thr} were set using literature values. The light extinction coefficient, k, was adjusted so that simulated total plant biomass for T5 equaled the observed value at H4. The calibrated value was 0.64, which is very close to the commonly used value of 0.65 (Neitsch et al. 2005). During this step, the observed biomass for T5 was the target, based on the assumption that plants in this treatment grew at nearly the potential rate.

[5] A Microsoft Windows based modeling environment developed by the U.S. Salinity Laboratory, U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), Riverside, California.

2. The waterlogging parameters P_0 and P_1 from equation 5-18 were adjusted until the simulated biomass value for T1 matched the observed value at H4. These values were set at -18 and -21 cm, respectively. These parameters were adjusted using the plants in T1 as the target because this treatment had the largest amount of waterlogging stress due to it having the slowest rate of water table decline. These values are within the range for coarse sand suggested by other researchers (Bartholomeus et al. 2008).

3. The drought stress parameters P_2 and P_3 from equation 5-18 were adjusted until the simulated biomass value for the plants in T2 matched the observed value for H4. These values were set at -39 and -42 cm, respectively.

4. The root growth parameters T_1, T_2, S_c, and S_L from equations 5-9 and 5-12 were adjusted until the root front velocity and root mass depth distribution matched the observed values from all treatments. Their values were 0.95, 0.85, 0.25, and 0.1, respectively.

Results from the calibration show the model simulated the observed biomass and maximum root depth values from H4 (tables 5-6 and 5-7). All values were within 5 percent of the observed values for T1, T2, and T5, which were the calibration targets. These treatments were used as calibration targets for biomass production because they survived the duration of the experiment and represented unstressed plants (T5), waterlogging stressed plants (T1), and drought stressed plants (T2). The simulated values for T3, which were not a calibration target, were less accurate, with the biomass value overpredicted by 20 percent and the maximum root zone depth overpredicted by 89 percent. The inaccuracy in the root depth suggests the root front velocity algorithm (equation 5-8) does not contain some necessary features. The root front extension rate, while initially increasing during periods of drought stress, may be limited during periods of severe stress, which would explain the relatively low observed value at H4.

Table 5-6. Observed and RHEM Simulated Per-Plant Biomass (mg) at H4 (Note: all T4 plants were dead by H4)

	T1	T2	T3	T4	T5
Observed	31.51	36.22	16.54		52.31
Simulated	30.94	34.68	19.81		52.52

Table 5-7. Observed and RHEM Simulated Maximum Root Depth (cm) at H4 (Note: all T4 plants were dead by H4)

	T1	T2	T3	T4	T5
Observed	44.29	59.09	40.00		43.13
Simulated	41.78	59.56	75.56		44.87

As the main purpose of the RHEM is to predict cottonwood seedling survival under drought stress, the accuracy of the calibrated model can also be judged by comparing predicted drought stress to observations of seedling stress and death. To do this, a plot was made of an average daily ET reduction factor, which represents the value of T_a/T_p when drought stress reduces the transpiration below potential (figure 5-3). From this plot, it can be seen that the simulated plant in T4 experienced drought stress starting July 7, 2008. By July 15, the stress factor had reached a value of less than 0.4. This coincides with the observed death of all seedlings in T4 (figure 5-2). The drought stress factor in T3 reached a value of 0.4 by July 28, which corresponds with the observation of complete plant death for this treatment (figure 5-2). The simulated plant in T2 started to experience drought stress on July 14. This stress increased through the end of the month and this corresponds with the decreasing plant survival observed for T2 (figure 5-2). This agreement between simulations and observations of drought stress and seedling death provides confidence that the model is simulating these processes well.

There is some variation in the ET reduction factor and some periods where the ET reduction factor increases because of varying climatic factors and there are periods where the water table is relatively constant or increasing. The plant can begin to recover during these periods.

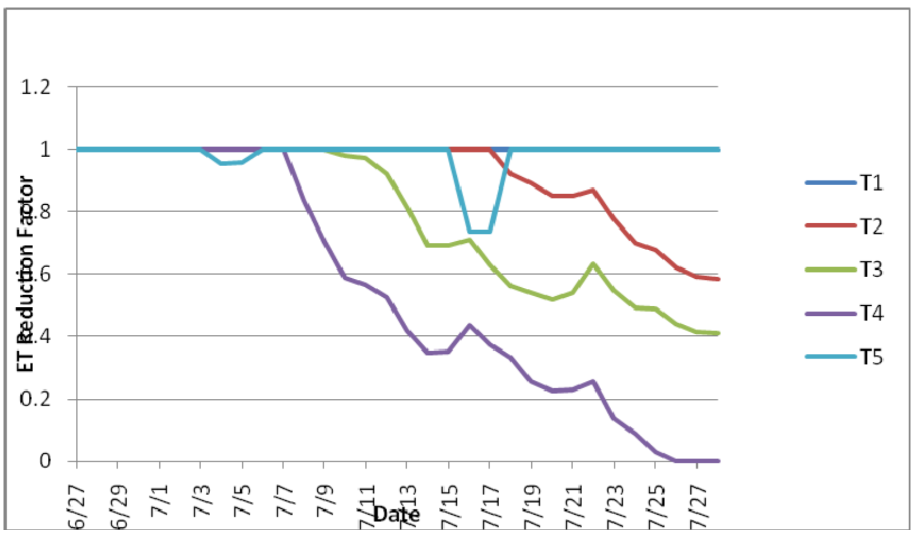

Figure 5-3. Daily average reduction in potential transpiration due to drought stress.

5.4 Validation

To validate the calibration of the cottonwood seedling growth model, simulations were compared with observations made by the authors during 2006 of seedling growth and death on a point bar located at RM 192.5 on the Sacramento River. The motivation for analyzing the differences in survival of cottonwood seedlings on these two sediment types was based on the findings of a higher rate of establishment on finer grained sediments such as silt and sand (Wood 2003).

Observations were made at two locations on the point bar with different sediment gradations:

- Location 1. Downstream end of the point bar where an eddy formed during high flow events and deposited fine sand and silt
- Location 2. Midpoint of the bar on coarse sediment consisting mostly of cobbles and gravel

At both locations, observation wells were installed and instrumented to record the water table depth on an hourly basis. The sites were visited periodically, and visual observations were made of seedling location, height, degree of stress, and death.

5.4.1 River Mile 192.5 – Sand

At Location 1 (with fine sand sediment), soil samples were collected and a laboratory analysis was conducted to determine the soil hydraulic properties. The soil water retention curve and associated van Genuchten parameters are presented in figure 5-4 and table 5-8.

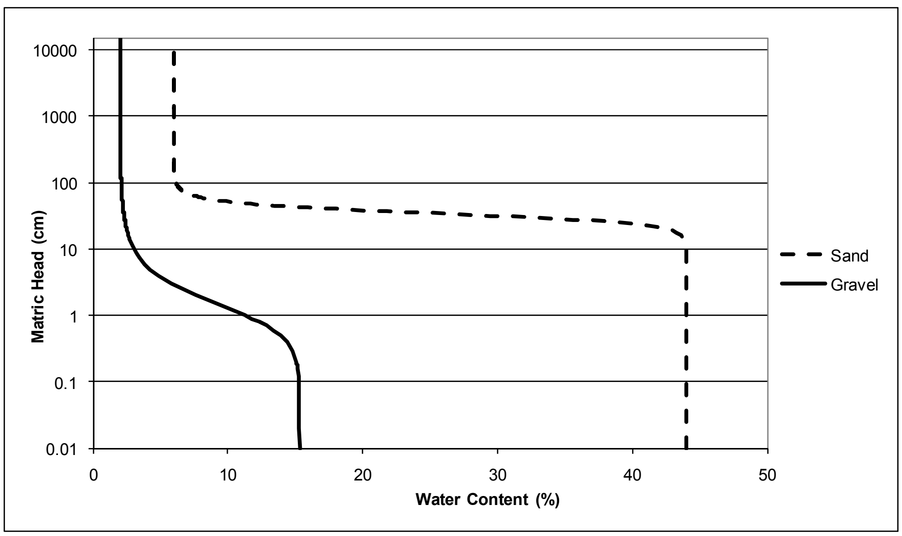

Figure 5-4. Soil water characteristics for gravel and sand soils located on Sacramento River point bar at RM 192.5.

Table 5-8. van Genuchten (1980) Parameters Used to Characterize Gravel and Sand Gradation Soils from Sacramento River Point Bar at RM 192.5.

	Residual volumetric water content	Saturated volumetric water content	Constants In the water retention model		Saturated flow hydraulic conductivity
	θ_r	θ_s	α (1/cm)	n	K_s (cm/d)[1]
Gravel	0.02	0.153	1.00	2.1	500
Sand	0.057	0.41	0.124	2.28	350

[1] cm/d = centimeters per day

The observed seedling at this location germinated around June 1, 2006. Seventy-six days later, on August 16, 2006, the seedling was harvested. Roots were harvested by driving a 2-inch pipe centered on the plant into the sediment, and then pulling it out of the soil. The sample was processed to determine dry root biomass, shoot biomass, leaf number, and root front depth. Leaf area was estimated visually to be approximately 50 to 75 square centimeters (cm^2).

During the growth of this seedling, the water table elevation was observed using a pressure transducer installed in a well located approximately 1.5 meters from the plant. Weather data including solar radiation, wind velocity, temperature, and relative humidity were obtained from the California Irrigation Management Information System (CIMIS) station located in Orland, California (station No. 61).

5.4.2 River Mile 192.5 – Gravel

The sediment in this location was a mix of cobbles up to 7 cm in diameter and gravel and very coarse sand. The measured porosity was 15 percent. Due to the coarseness of this sediment, it was not possible to measure the soil moisture release curve; therefore, the curve presented in figure 5-4 and table 5-8 is an estimate based on the assumption that gravel has larger values of α and K_s and smaller residual water content (θ_r) compared to sand (Idaho National Engineering and Environmental Laboratory 2001). Also, due to the coarseness of the sediment in this location, intact plant samples were not collected. Similar to the location on fine sediments, an observation well was installed to provide measurements of water table depth in the vicinity of the seedlings. Weather data were obtained from CIMIS station No. 61.

The observed seedlings at this location germinated within days of June 8, 2006. By July 12, the seedlings were 3 to 8 cm in height but showed a lack of vigor—presumably due to water stress. By July 26, the seedlings were very stressed, with approximately 50 percent of the seedlings reported dead. Subsequent observations through August 25 indicate that the remaining seedlings continued to grow to a height of 5 to 10 cm but remained stressed. On September 7, it was reported that nearly all the seedlings were dead. By October 3, all the seedlings were reported dead.

5.4.3 Validation Results

The RHEM simulation predicted a smaller seedling than that observed on the sand at RM 192.5 (table 5-9). Total biomass of the simulated seedling was 62 percent less than the observed value. The observed root mass ratio (root mass/plant mass) was 0.37. The modeled root mass ratio was somewhat higher (0.41). The large difference between the observed and simulated values for biomass may be because only a single seedling was collected from this cohort, which contained 100+ seedlings. Observations made on August 25, 2006, indicate that seedlings in this cohort ranged from 10-20 cm in height, which suggests there was a large range in total biomass among individual plants. On the gravel sediment, the simulated seedling was smaller and had a total biomass of 279 mg and a leaf area of 24 cm^2 on August 16. This is in general agreement with recorded observations that indicate, on August 25, the cohort of seedlings on the gravel sediment was half the height (5-10 cm) of the seedlings on the sand sediment.

Table 5-9. Observed and Modeled Plant Growth Values for a Seedling on Sand Sediment Located at RM 192.5 (June 1-August 16, 2006)

	Plant Mass (mg)	Shoot Mass (mg)	Root Mass (mg)	Leaf Area (cm^2)	Root Zone Depth (cm)
Observed	915	571	344	50-75[1]	75
Modeled	345	202	143	30	74

[1] Estimated value

While the comparison of biomass production indicates that RHEM may not be highly accurate with respect to plant size, validation results shows that RHEM is able to accurately predict root zone depth and seedling mortality resulting from dessication. This is of more importance to the application described in this document, as the analysis goal is to determine the survival of seedlings under various water management schemes. Comparisons of the ET reduction factor caused by drought stress show that the seedling on the gravel reached a value of 0.4 on August 27 and perished on August 29 (figure 5-5). This simulation result agrees with observations made in the field, which recorded that seedlings on the gravel sediment were alive on August 25 but were nearly all dead by September 9.

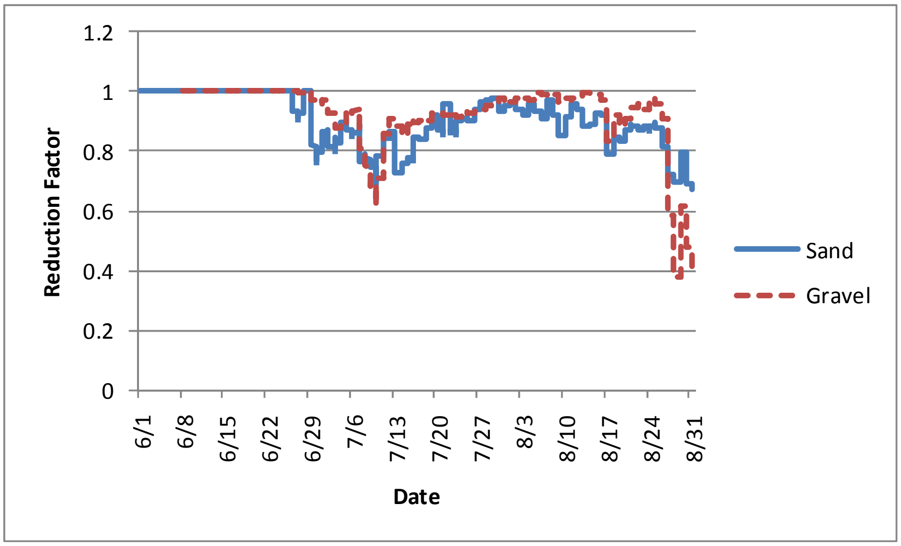

Figure 5-5. Comparison of ET reduction factor due to drought stress for seedlings grown on sand and gravel at RM 192.5 on the Sacramento River during 2006.

In contrast, the seedlings on the sand sediment were reportedly stressed but alive. The cause of the seedling death on the gravel was likely a rapid drop in the Sacramento River stage, which resulted in a water table decline of 5 cm/d for a period of 4 days. This rapid drop in river stage started on August 23. In RHEM, the reduction factor was reduced to less than 0.4 on August 27. The fact that the simulated seedling died 4 days after the initiation of the stress suggests that the measured seedling managed to transpire at nearly the full rate for a few days using water remaining in the soil after the water table lowered.

5.5 Determining the Parameters for SRH-1DV

The ultimate goal of the research and modeling effort described here was to provide information useful for Reclamation's SRH-1DV model, which will be used to study the establishment of cottonwood seedlings along a 100-mile reach of the Sacramento River. To provide usable information about seedling survival, a series of numerical experiments was conducted using RHEM code, in which the effect of different water table decline rates on simulated seedling survival was simulated. These numerical experiments were conducted using the soil physical properties for sand and gravel sediments found on the point bar at RM 192.5. Both sand and gravel were studied in order to explore the differences in seedling survival between the two sediment types.

Numerical experiments were conducted using a fixed set of atmospheric boundary conditions and a range of water table decline rates. Experiments were devised to simulate both the imposition of drought stress caused by a falling water table and the reduction or recovery from stress caused by a rising water table. The stress caused by the falling water table was termed “desiccation,” and the reduction in stress caused by the rising water table was termed “recovery.”

A single day of hourly atmospheric variables was repeated during the entire simulation in order to remove variations in the results caused by changes in the weather. June 15, 1994, was chosen from the CIMIS Station No. 61 historical record because it represented one of the largest daily average rates of reference evapotranspiration (ETo) for the station. This was done to represent the maximum stress possible on the simulated seedlings. In these experiments, the plant’s ability to deal with water stress was tested after the plants had 32 days to establish. This was done based on observations by California Department of Water Resources (CDWR) and the authors suggesting that fatal drops in river stage occurred later in the summer after the plants had some time to develop (Morgan and Henderson 2005). For the desiccation experiments, the water table was held at a constant depth of 5 cm for the first 3 days as the plant germinated and established its root system. During the second period (14 days), the water table was lowered at a rate of 1 cm/d. For the third period (15 days,) the water table was lowered at a rate of 0.5 cm/d. Following this third period, the experiment was initiated, and the water table was lowered a fixed amount every day until plant death occurred.

A plot of the ET reduction factor for the plants on the sand sediment shows how the plants responded to the different water table decline rates (figure 5-6). The plants took longer to perish with slower water table decline rates. For instance, the plant perished in 20 days with a 2-cm/d water table decline and in only 3.3 days with an 8-cm/d water table decline.

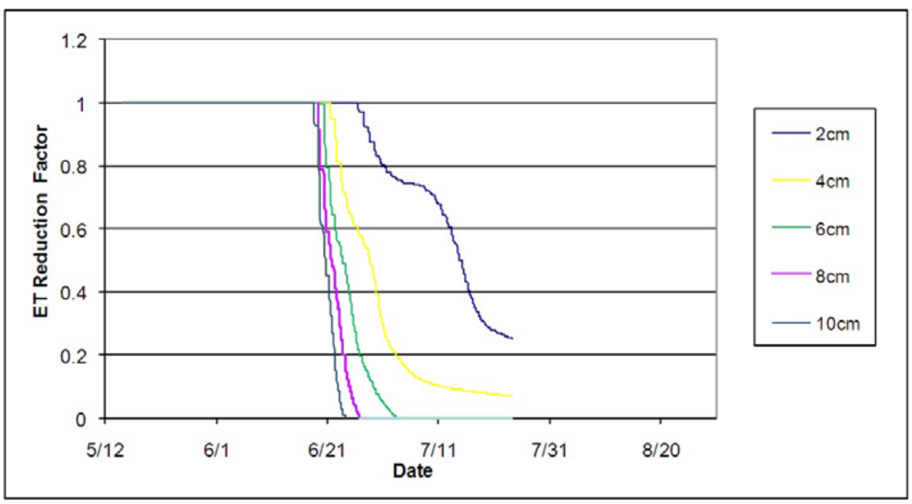

Figure 5-6. ET reduction factor for various daily water table decline rates for the sand sediment type.

For the recovery experiments, the water table was held at a constant depth of 5 cm for the first 3 days as the plant germinated and established its root system. During the second period (14 days), the water table was lowered at a rate of 1 cm/d, and during the third period (15 days), the water table was lowered at a rate of

0.5 cm/d. For the plants on the sand sediment, the water table was then lowered 7 cm/d for 8 days in order to stress the plants to near death. For the gravel sediment, after the third period, the water table was lowered 4 cm/d for 3 days, and then held constant for 1 day. This resulted in enough drought stress on the plants that the ET reduction factor was reduced to 0.44 for the sand and 0.46 for the gravel. In both cases, the experiment was started, and on the following days, the water table elevation was increased at a fixed rate. The ET reduction rate for the sand sediment is shown in figure 5-7. Recovery took longer for lower rates of water table increase. In one example, the plant fully recovered in 15.4 days for the 2-cm/d increase in water table elevation under an ET reduction factor equal to 1.0. The plant fully recovered in 3.4 days with the 10-cm/d increase in water table elevation.

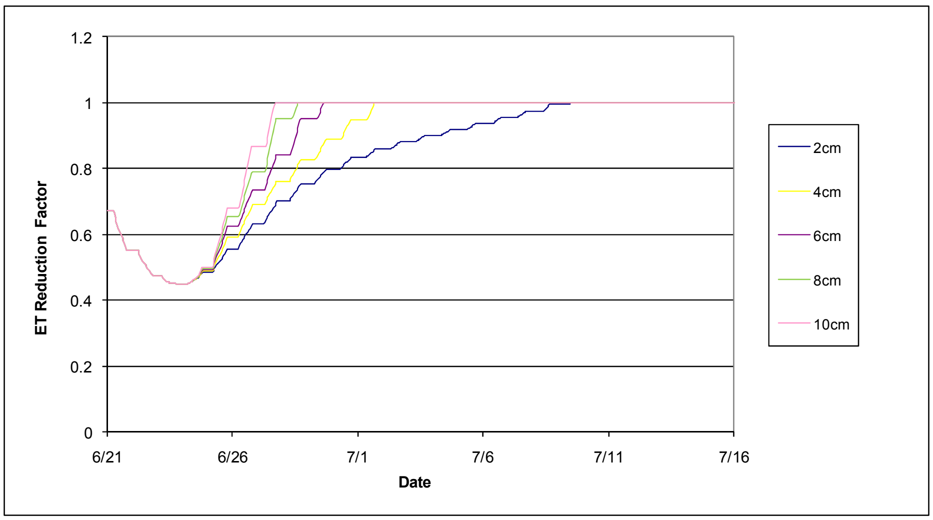

Figure 5-7. Recovery of ET reduction factor for different rates of daily water table elevation increase.

A comparison of the desiccation and recovery rates for sand and gravel sediment is presented in figure 5-8.

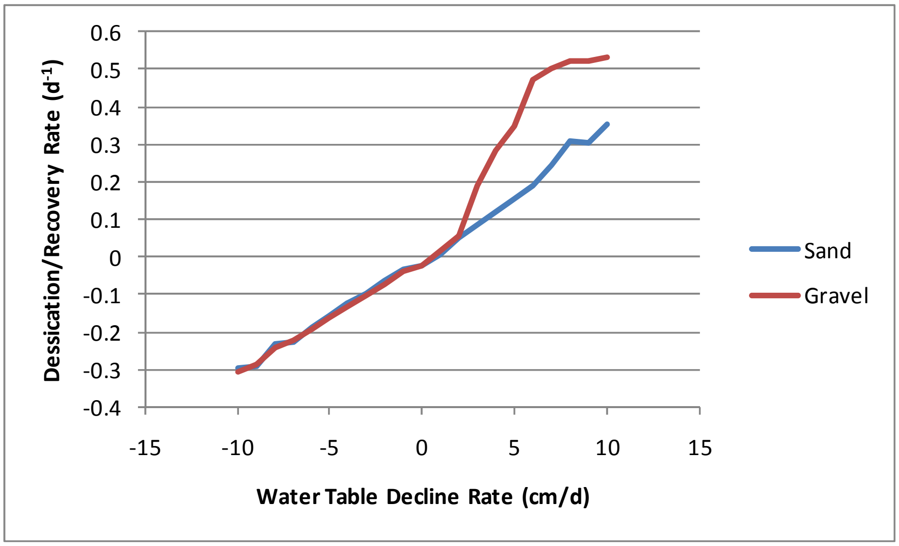

Figure 5-8. Desiccation and recovery rates for sand and gravel sediment as a function of water table decline rate.

An example of how to interpret this graph is that cottonwood seedlings growing in the sand sediment will take over 6 days to die if the water table drops at 5 cm/d. On gravel sediment, the plants will take about 3 days to die at the same rate of water table decline. Differences in these values were expected due to the differences in the soil hydraulic properties. The sand sediment has a greater water holding capacity in the root zone above the capillary rise zone than the gravel sediment. Both root growth and water holding capacity of the soils would result in more water available for plant use within the soil profile. For water table decline rates of 2 cm/d and less, the ability of the roots to grow deeper at a similar rate resulted in much less stress and little difference between the sediment types. It is interesting to note that recovery rates (e.g., where the water table decline rate is less than 0) are nearly identical for both sediment textures. This is probably due to the rapid rate of water movement in the soil types as the water table rises.

The RHEM model for predicting cottonwood desiccation mortality, based on plant stress and recovery in sand or gravel soils, was incorporated into the final runs of the sediment transport and vegetation growth model, SRH-1DV. Stress rates on seedling cottonwood plants are tracked within SRH-1DV and the young plants are removed when the rates shown in figure 5-8 are exceeded. SRH-1DV is described in detail in Chapter 6.

5.6 Concluding Remarks

The controlled field experiments and modeling described above provide a detailed analysis of cottonwood seedling growth and survival when moisture is limited. The RHEM is able to simulate seedling growth with a reasonable degree of accuracy using the calibration data set. RHEM is also able to predict seedling survival when the plants are moisture limited using the validation data set, which was based on limited observation data. However, results from the validation suggest that some aspects of the algorithms need further refinement to accurately predict seedling growth parameters. In particular, the root front velocity algorithm may need to be redesigned to account for severe water stress and reduce the maximum root front velocity in this situation. The numerical experiments studying the effect of different water table decline rates show a significant difference in the ability of seedlings to survive on sand versus gravel sediment. This conclusion is in agreement with observations made by others (Wood 2003), and this study provides a quantification of those differences useful for modeling seedling survival on the Sacramento River. The RHEM model has been incorporated into the Sacramento River SRH-1DV model to compute desiccation mortality for young cottonwood plants.

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