An Integrated Model of Water Flow in Soil-Plant Systems

Recep Kaya Göktaş

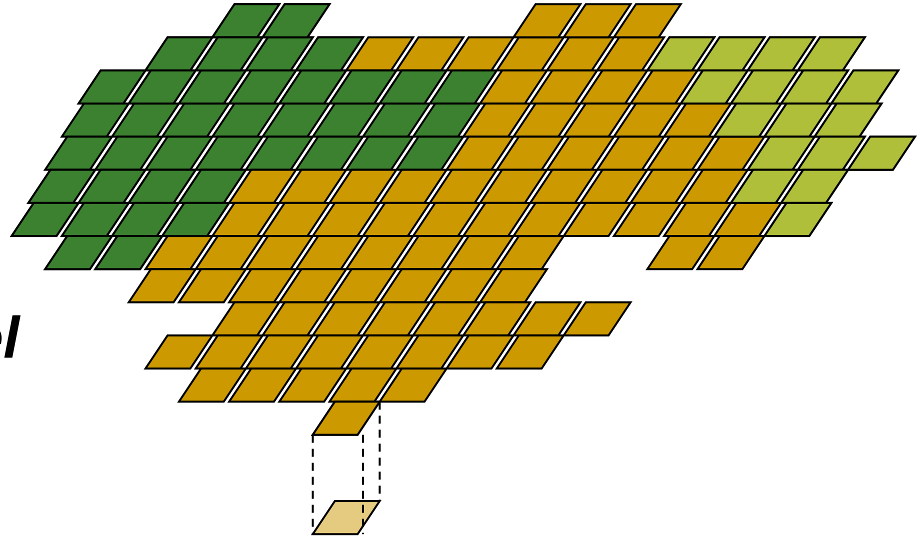
MESL Group Seminar
10/25/2010

Objectives

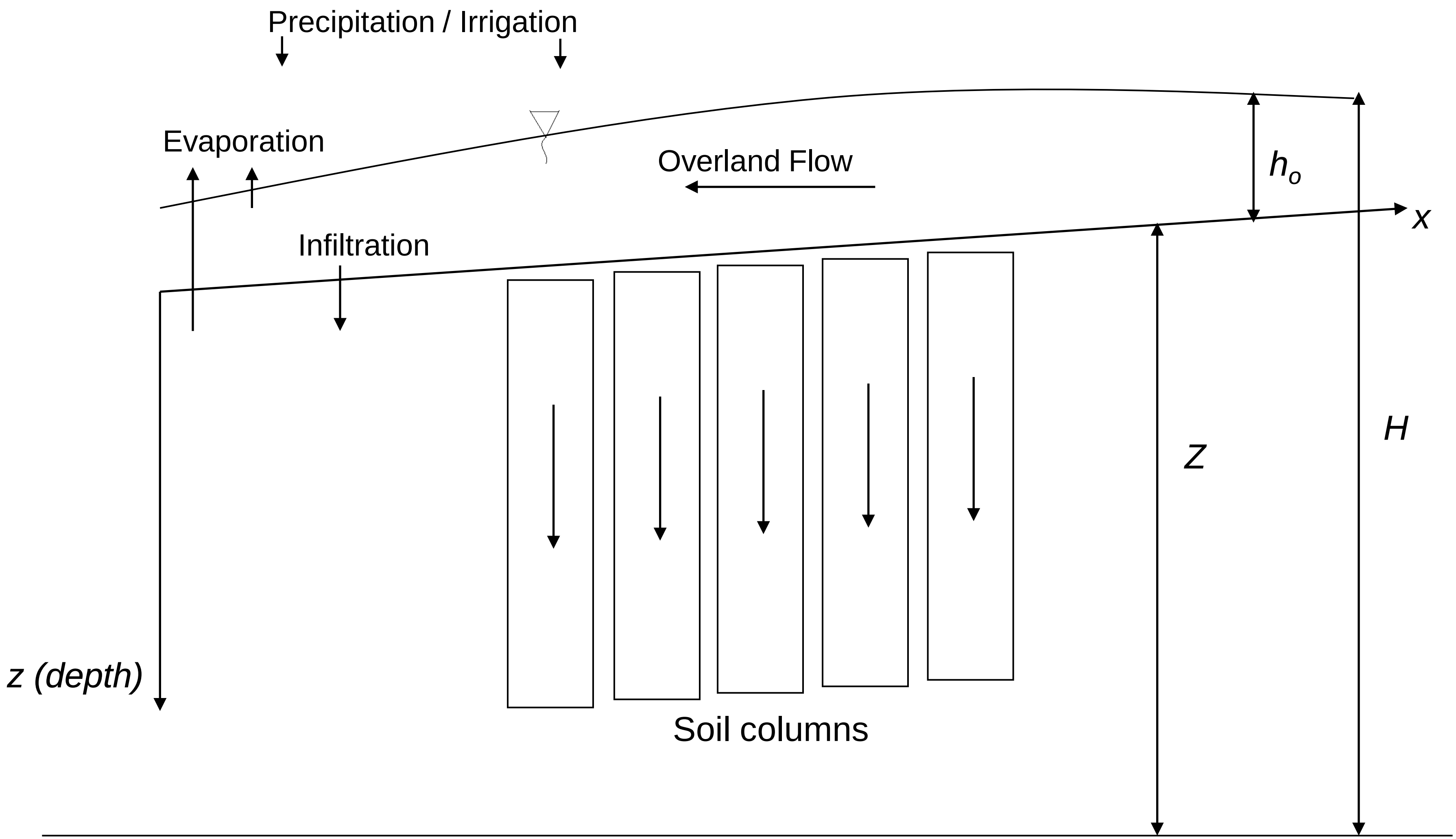
- Develop a model of water flow in a terrestrial system that
  - can describe water flow on the land surface and within the shallow soil for extended periods of time
  - takes into account the effects of the presence of vegetation on the overall water flow dynamics within the system
  - treats vegetation as a dynamic entity considering
    - its life cycle
    - its response to water availability within the system
- Develop a tool
  - for prediction of surface runoff
  - for prediction of infiltration
  - that can be further combined with contaminant transport models

Modeling Approach

- The modeling domain is represented by a collection of soil-plant system units.
- The soil-plant system units are coupled through
  - An ***overland flow model*** to represent ground surface flow processes.
  - Accounting for the ***lateral flow fluxes*** between the corresponding soil layers.



Schematic View of the Integration



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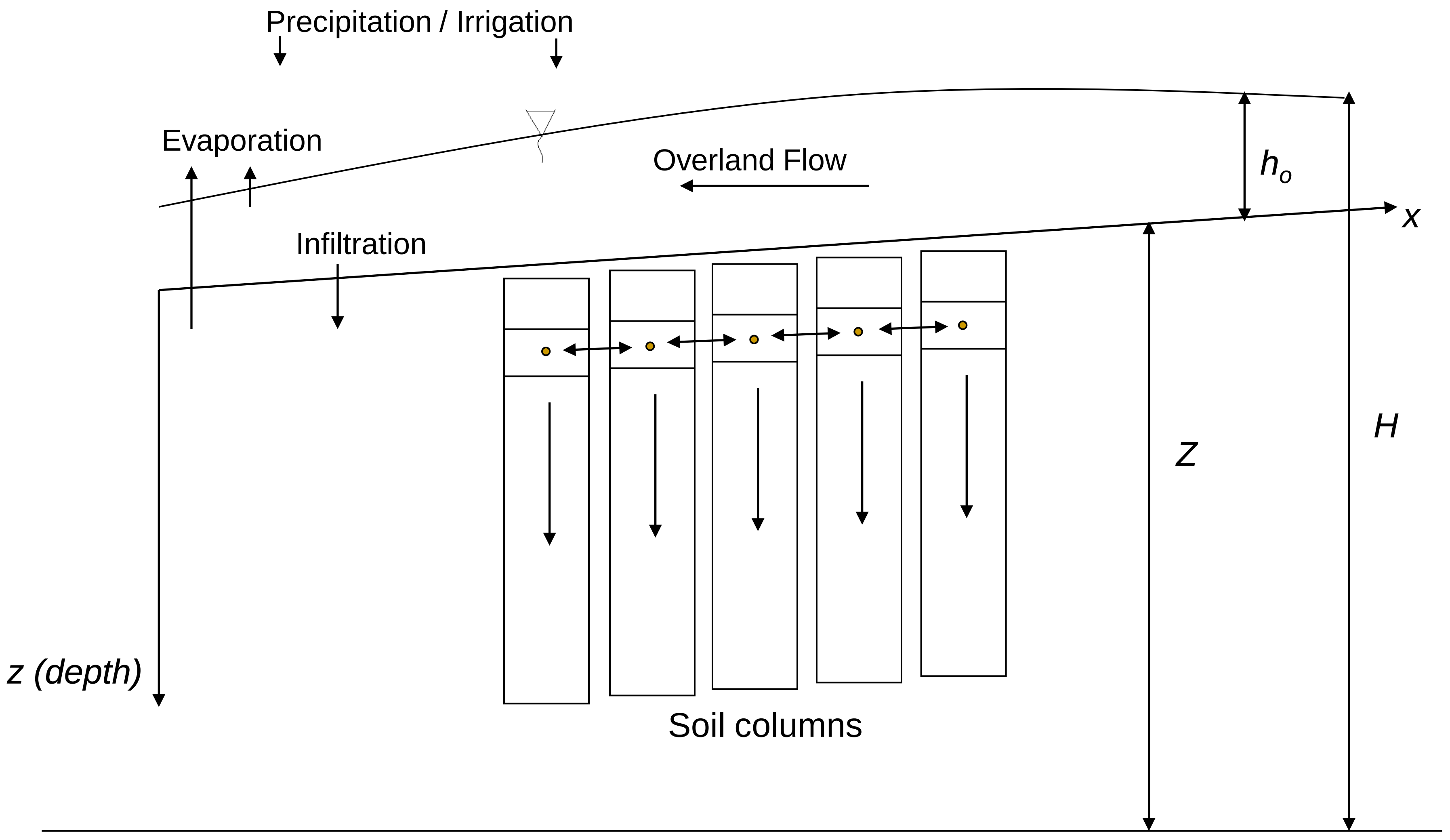


Integrated Flow Model

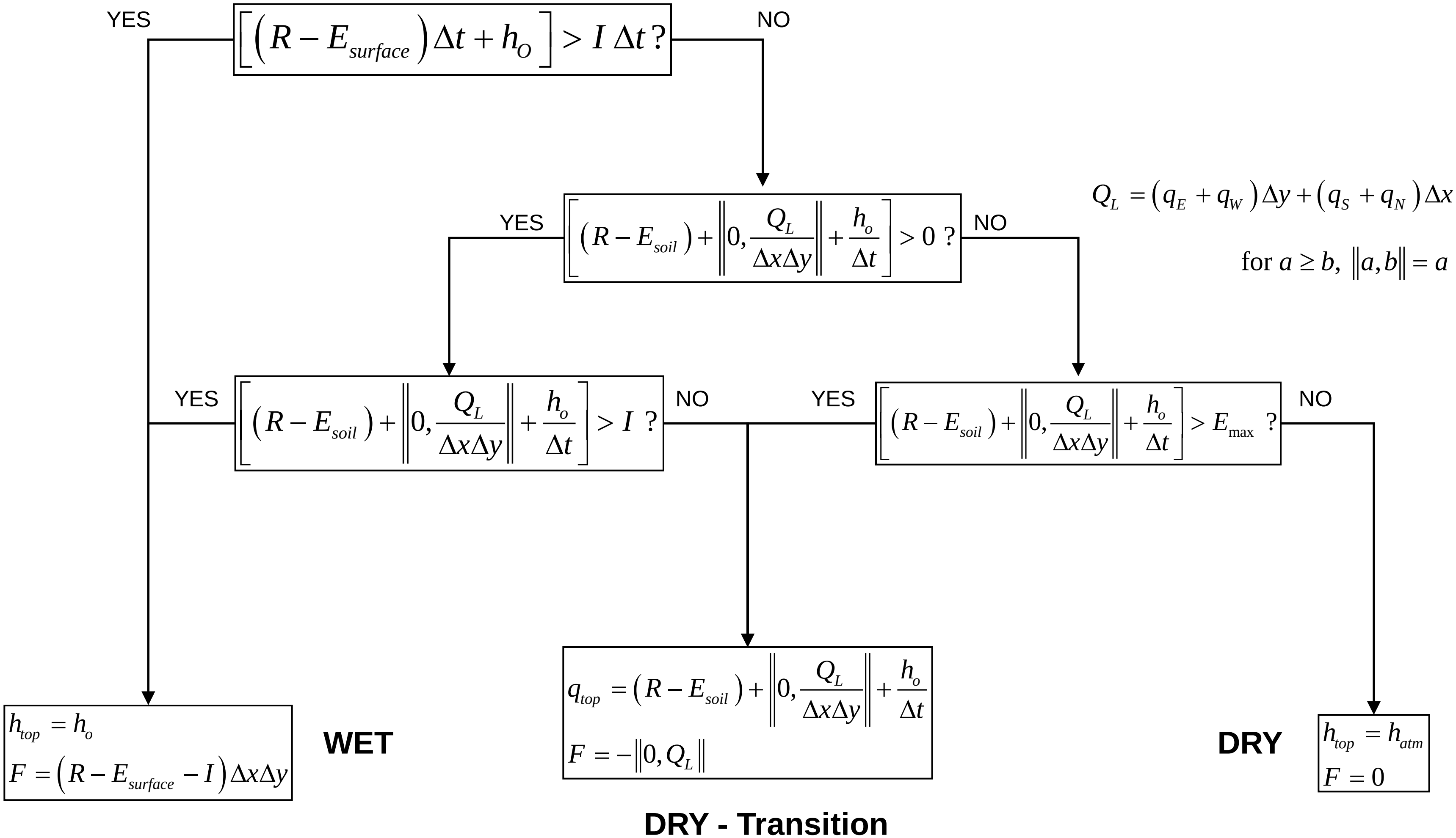
- Overland flow model

  2D non-inertial-wave (diffusion wave) approximation to the Saint-Venant equations

- Unsaturated zone soil-water flow model coupled with the plant life-cycle model
- Subsurface lateral fluxes

  Darcy fluxes between corresponding soil cells in adjacent columns

Overland / Subsurface Interaction Algorithm



$$I = \left[-K_{1/2} \left(\frac{h_1 - h_o}{0.5 \Delta z_1} - 1 \right) \right]$$

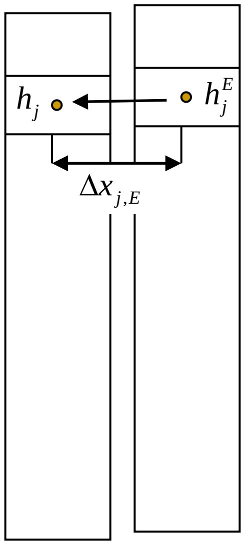
h_{atm}: soil-water pressure head in equilibrium with the prevailing relative humidity in the atmosphere [L]

$$E_{\max} = -K_{1/2} \left(\frac{h_1 - h_{atm}}{0.5 \Delta z_1} - 1 \right)$$

Subsurface Lateral Fluxes

Lateral flux into cell *j* from EAST:

$$q_j^E = K_j^E \frac{h_j^E - h_j}{\Delta x_{j,E}}$$



K_j^E : The interblock hydraulic conductivity at the EAST interface of cell *j*. [L T^{-1}]

h_j : Pressure head value at cell *j*. [L]

h_j^E : Pressure head value at the EAST neighbor of cell *j*. [L]

$\Delta x_{j,E}$: The distance between the centers of cell *j* and its EAST neighbor. [L]

Spatially discretized soil-water flow equation with the lateral fluxes added:

$$M_j \left(\frac{dh}{dt} \right)_j + S_j^1 h_{j-1} + S_j^2 h_j + S_j^3 h_{j+1} = F_j + q_j^E + q_j^W + q_j^N + q_j^S$$

LINEARIZATION OF THE vGM MODEL NEAR SATURATION

Richards' Equation:

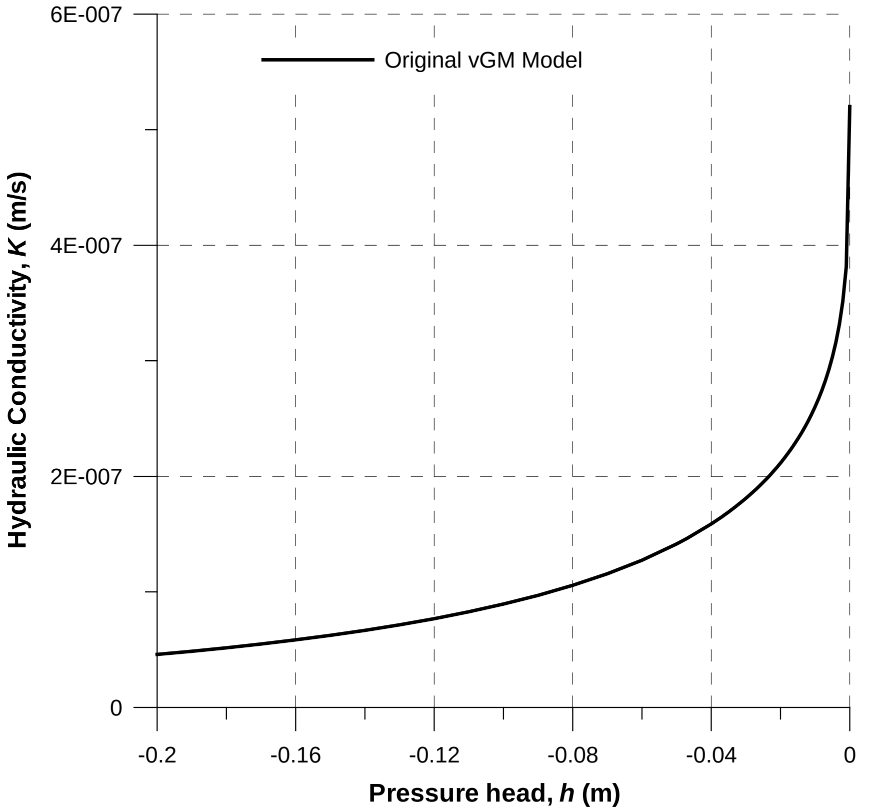
$$C\frac{dh}{dt}=\frac{\partial}{\partial z}\left(K\left(\frac{\partial h}{\partial z}-1\right)\right)-U$$

vGM Model:

$$S_e(h)=\frac{\theta(h)-\theta_r}{\theta_s-\theta_r}=\left[1+\left(\alpha_v\left|h\right|\right)^{n_v}\right]^{-m_v}$$

$$K(h)=K_s\left(S_e(h)\right)^{1/2}\left[1-\left(1-\left(S_e(h)\right)^{1/m_v}\right)^{m_v}\right]^2$$

vGM model for a fine-textured soil



$\theta_s = 0.41$, $\theta_r = 0.05$, $n_v = 1.31$, $\alpha_v = 1.9$, $K_s = 5.2 \times 10^{-7}$ *m/s*

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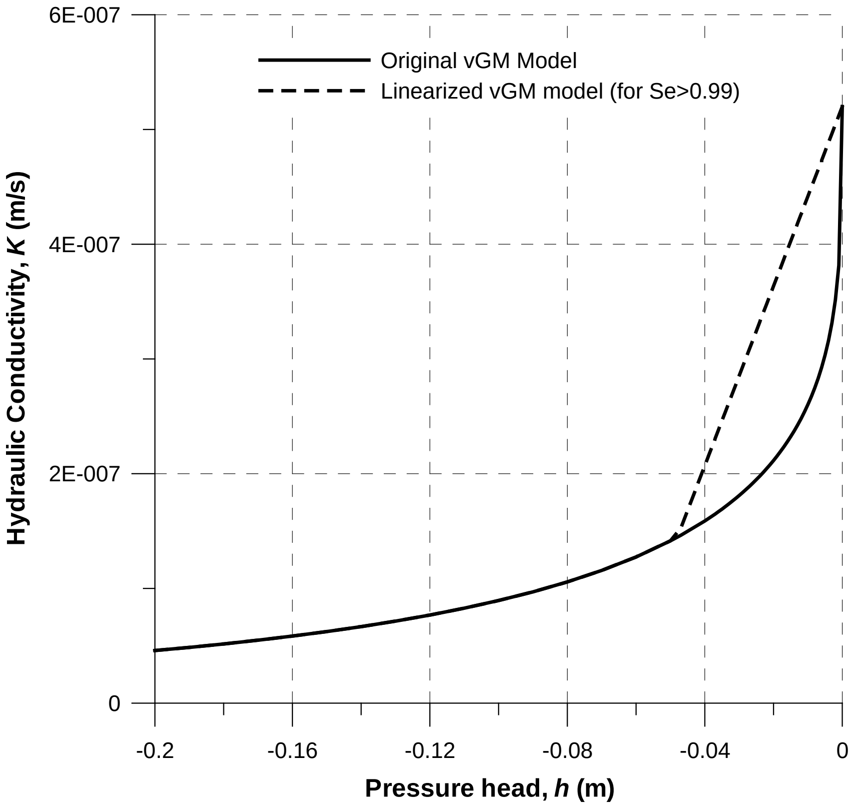
linearized *K*: *K*(*h*)*

$$\frac{h-h^{0.99}}{0-h^{0.99}}=\frac{K\left(h\right)^{*}-K\left(h^{0.99}\right)}{K_s-K\left(h^{0.99}\right)}$$

vGM model for a fine-textured soil



θ_s = 0.41, θ_r = 0.05, n_v = 1.31, α_v = 1.9, K_s = 5.2 × 10^{-7} *m/s*

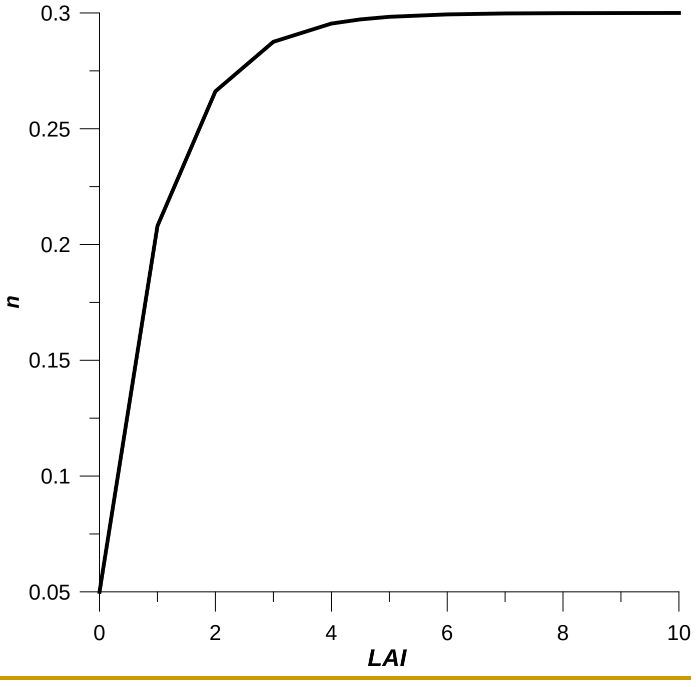
Effect of Vegetation on Overland Flow

The Manning's roughness coefficient variation due to plant growth:

$$n = \left(n_{\max} - n_{\min}\right)\left[1 - \exp\left(-LAI\right)\right] + n_{\min}$$

adopted from *Mailhol and Merot* (2008)

n : Manning's roughness coefficient. [T $L^{-1/3}$]
n_{max} : Maximum value of n when the crops are mature (when $LAI = LAI_{max}$). [T $L^{-1/3}$]
n_{min} : Minimum value of n when there are no crops (when $LAI = 0$). [T $L^{-1/3}$]
LAI : Leaf area index value. [L^2 L^{-2}]



Effect of Vegetation on System Hydrology

Soil Evaporation

$$E_p = \left(1 - f_c\right) E_{p,0}$$

Transpiration

$$T_p = f_c ET_p - E_{\text{int}}$$

Interception Storage

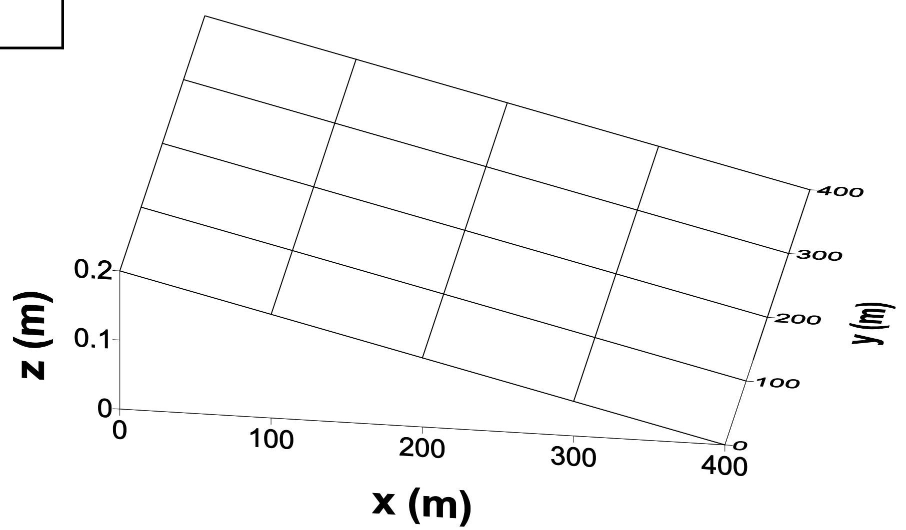
$$S_{\text{int,max}} = LAI \cdot S_L$$

f_c : Vegetation cover fraction [L^2 L^{-2}]
$E_{p,0}$: Potential evaporation rate for bare, wet soil according to the site conditions [L T^{-1}]
ET_p : Potential evapotranspiration rate representing the combined effect of the evaporation and transpiration processes occurring at the site [L T^{-1}]
E_{int} : Evaporation rate from interception [L T^{-1}]
S_L : Specific storage capacity [L]

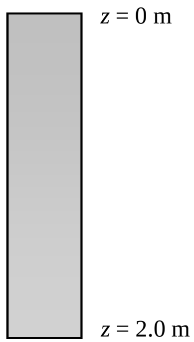
Model Application

The overland flow domain

Slope in *x*-direction	0.0005
Slope in *y*-direction	0.0
Length in *x*-direction	400 m
Length in *y*-direction	400 m
Boundary condition	Zero-depth gradient outlet at x = 400 m Other sides are no-flow boundaries
Initial condition	Dry
Spatial discretization, Δy	100 m (ny = 4)
Spatial discretization, Δx	100 m (nx = 4)

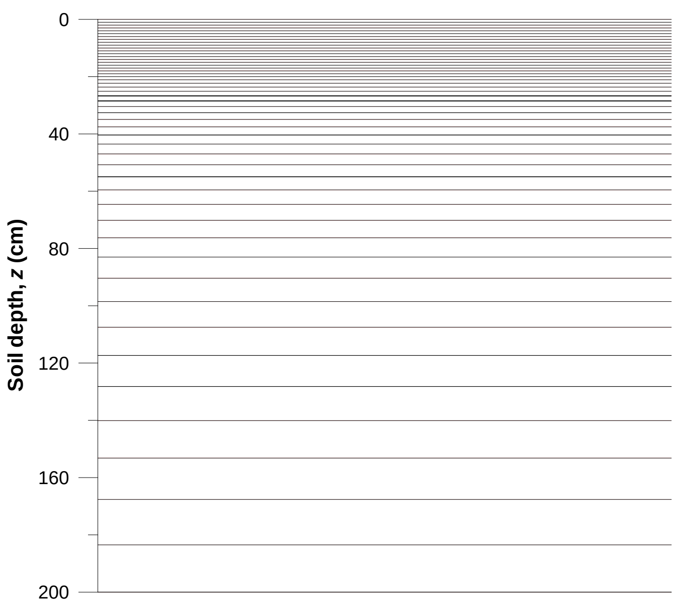


Model Application



B.C.: free drainage

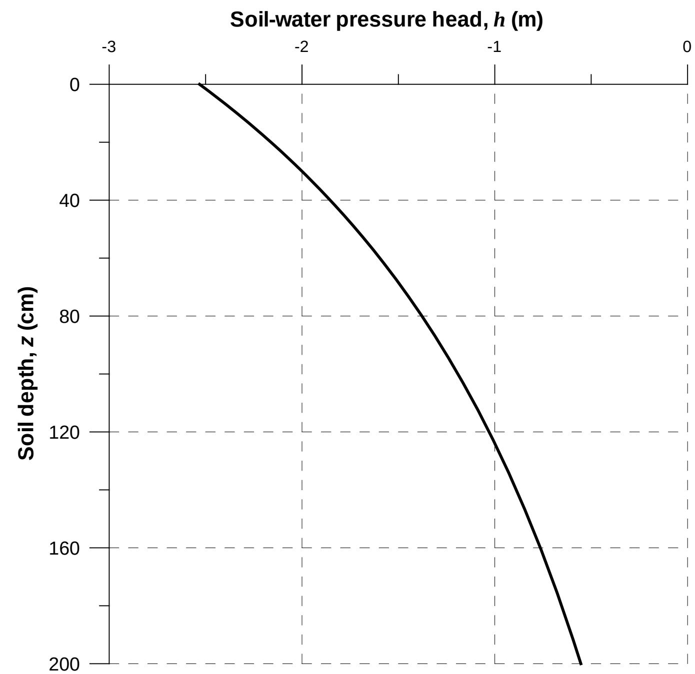
Soil Cell Thicknesses



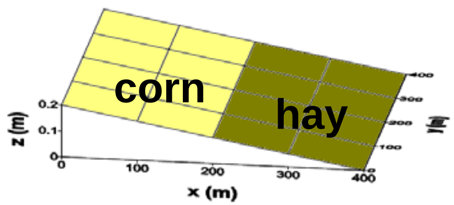
Soil characteristics (silt loam):

Saturated hydraulic conductivity, K_{sat}	1.25×10^{-6} m/s
van Genuchten parameters	$n = 1.41$ $\alpha = 2.0$ 1/m $\theta_{res} = 0.067$ $\theta_{sat} = 0.45$

Initial Condition:



Plant Parameters



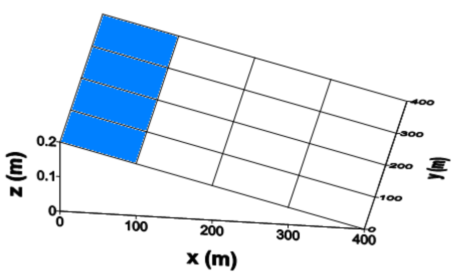
	Parameter	Corn	Hay
		(Mailhol, Olufayo et al., 1997; Wohling and Mailhol, 2007)	(Mailhol & Merot, 2008)
LAI related	LAI_{max} (m^2m^{-2})	4.5	8
	T_b(C)	6	0
	T_s(C)	100	0
	T_f(C)	1005	900
	l	1.25	10
	b	2.4	3
	d_1	14	3.7
	d_2	0.2	4.4
Biomass related	T_{mat}(C)	1925	1020
	RUE(gMJ^{-1})	1.32	0.37
Root related	L_R (0)	0.1	0.1 (assumed)
	$L_{R,.max}$ (m)	1.2	0.5 (assumed)
	t_R (days)	72	50
Evapotranspiration related	$K_{c,max}$	1.2	1
	x_k	1	1
	k	0.7	0.65
Overland flow related	n_{max}	0.15 (Assumed)	0.3

Weather Data

Air temperature (*T*)	20°C
Reference evapotranspiration (ET_0)	2.5 mm/day
Reference evaporation rate from bare soil, ($E_{p,0}$)	2.0 mm/day
Evaporation rate from free water surfaces ($E_{w,0}$)	3.0 mm/day
h_{atm}	-160 m

Irrigation Schedule

- 6-hour irrigation period every 10 days starting at day 1.
- Two irrigation methods:
  - **Border irrigation**
    The water is input to the upper cells that are bordering the *x=0 m boundary*.
  - **Sprinkler irrigation**
    The water is distributed uniformly to the *whole overland domain*.

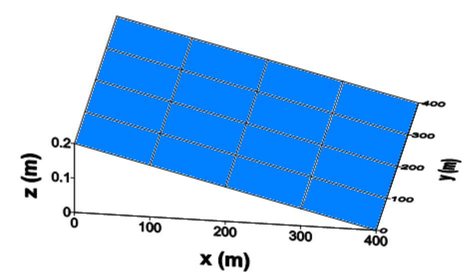


Border Irrigation

Discharge rate (mm/hour)	**13.5**
Discharge time (hours)	6
Border cells area (m^2)	40000
Discharge Volume (m^3)	3240

Sprinkler irrigation

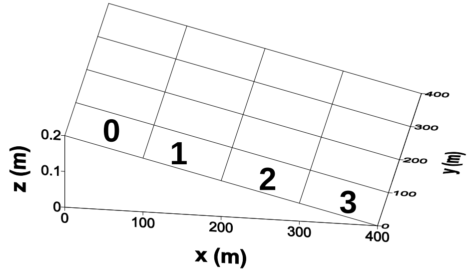
Discharge rate (mm/hour)	**3.375**
Discharge time (hours)	6
Area (m^2)	160000
Discharge volume (m^3)	3240



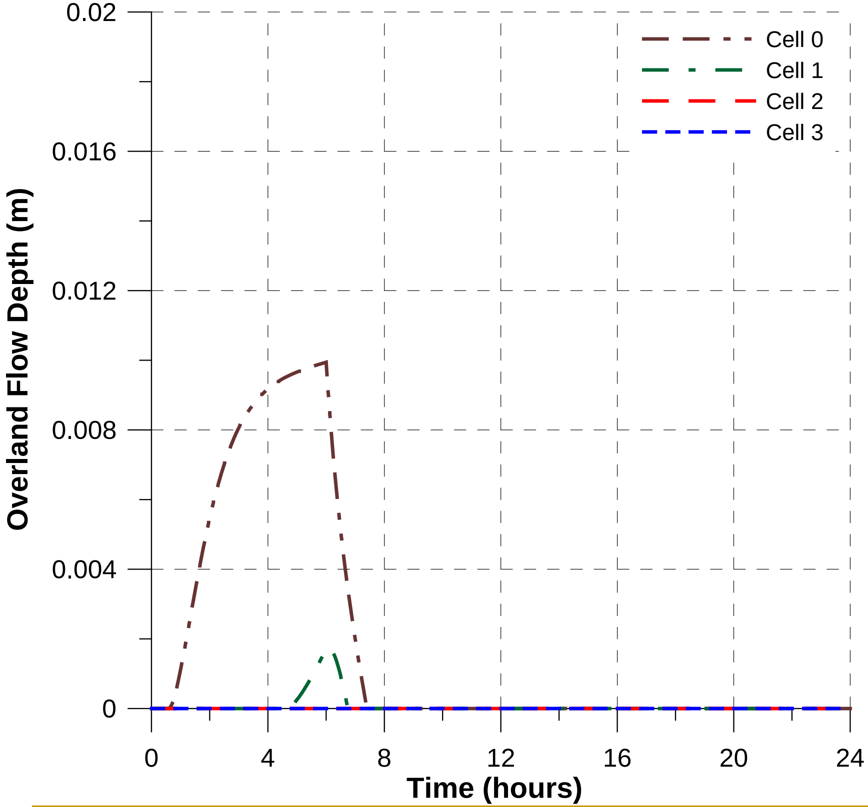
Classification of the Simulations

- Simulation Length
  - Daily (simulation length = 1 day)
  - Seasonal (simulation length = 120 days)
- Irrigation Method
  - Border Irrigation
  - Sprinkler Irrigation
- Plant Simulation
  - No Plant (Bare soil)
  - Const. Plant (corn: *LAI* = 3.0, hay: *LAI* = 5.0)
  - Plant (Plant life-cycle simulated)

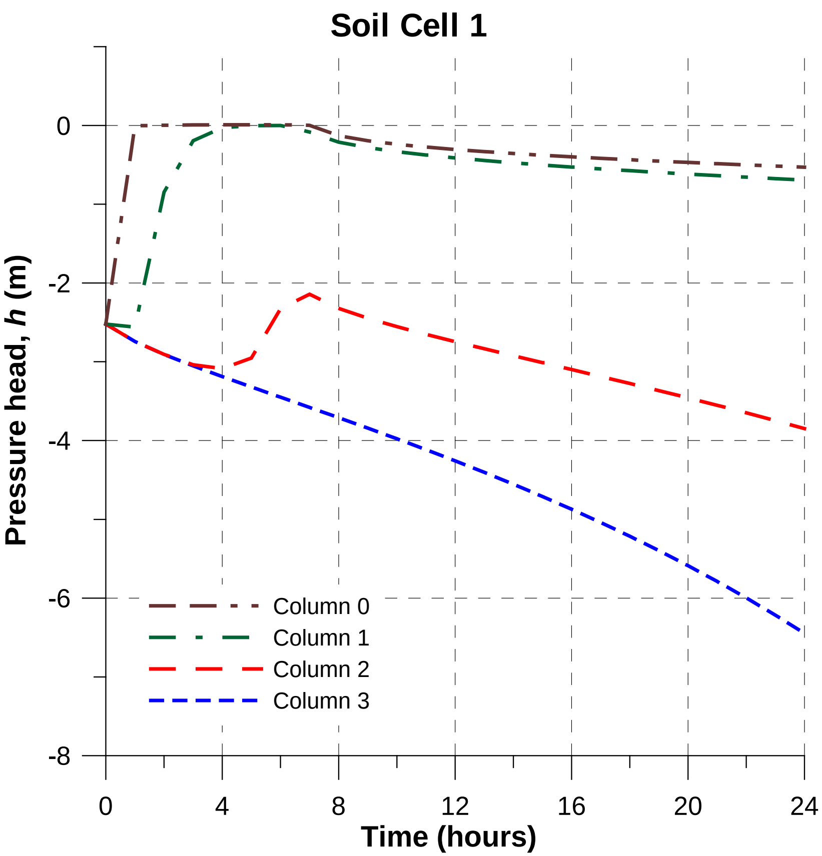
Daily Simulations
BORDER IRRIGATION (No Plant)



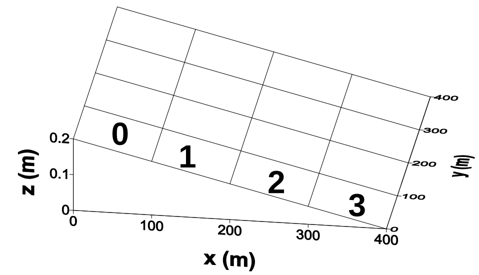
Overland Flow Depth Variation with Time



Pressure Head Variation at the Top Soil Cell



Daily Simulations
BORDER IRRIGATION (Const. Plant)



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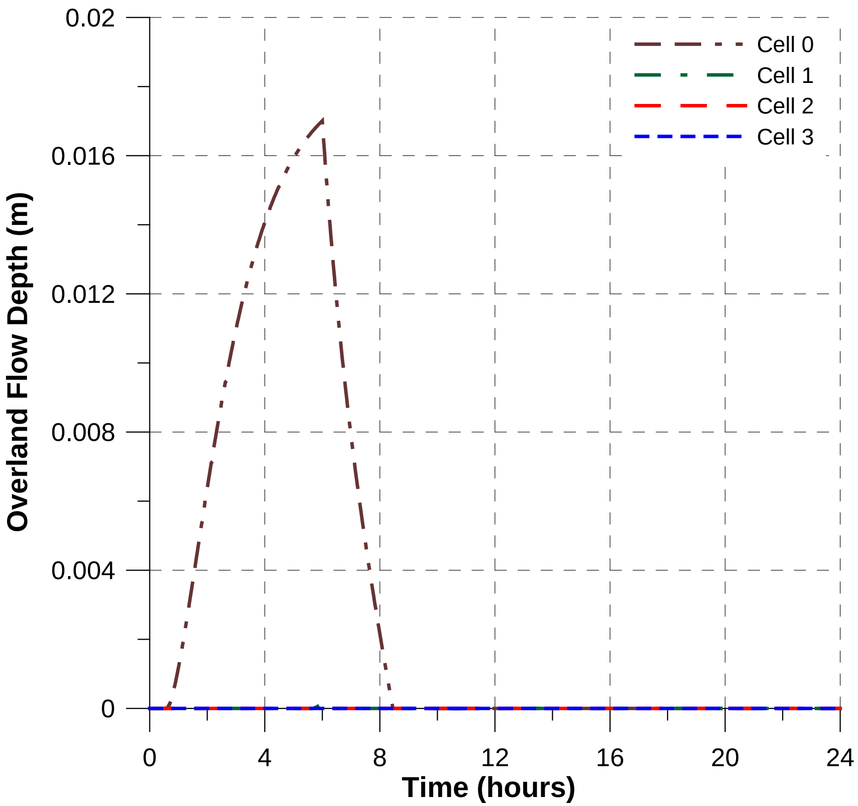

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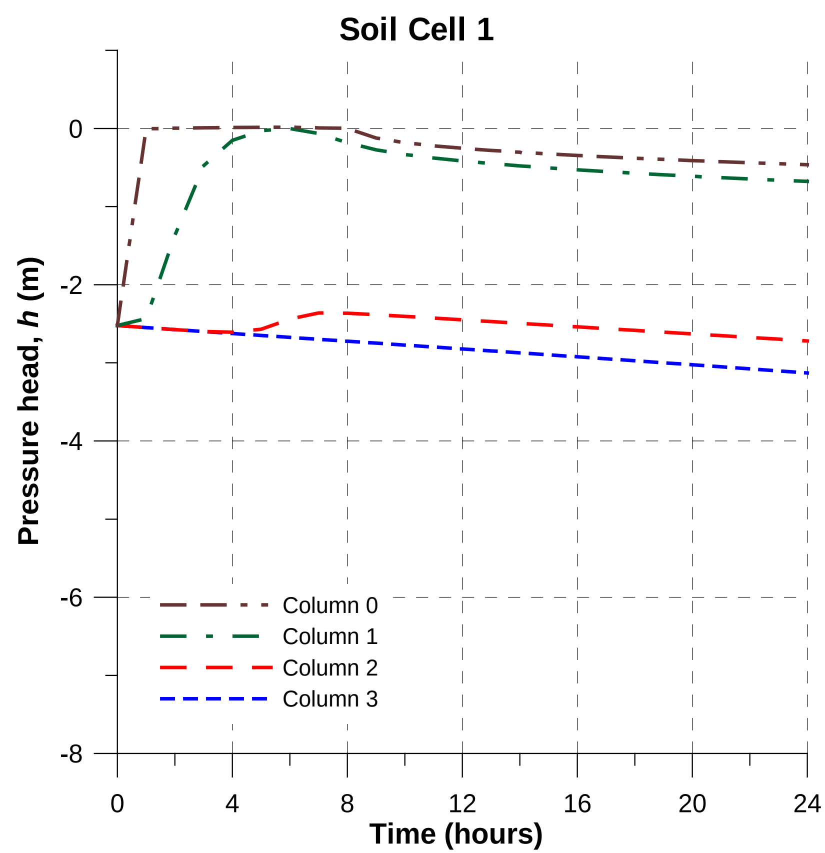
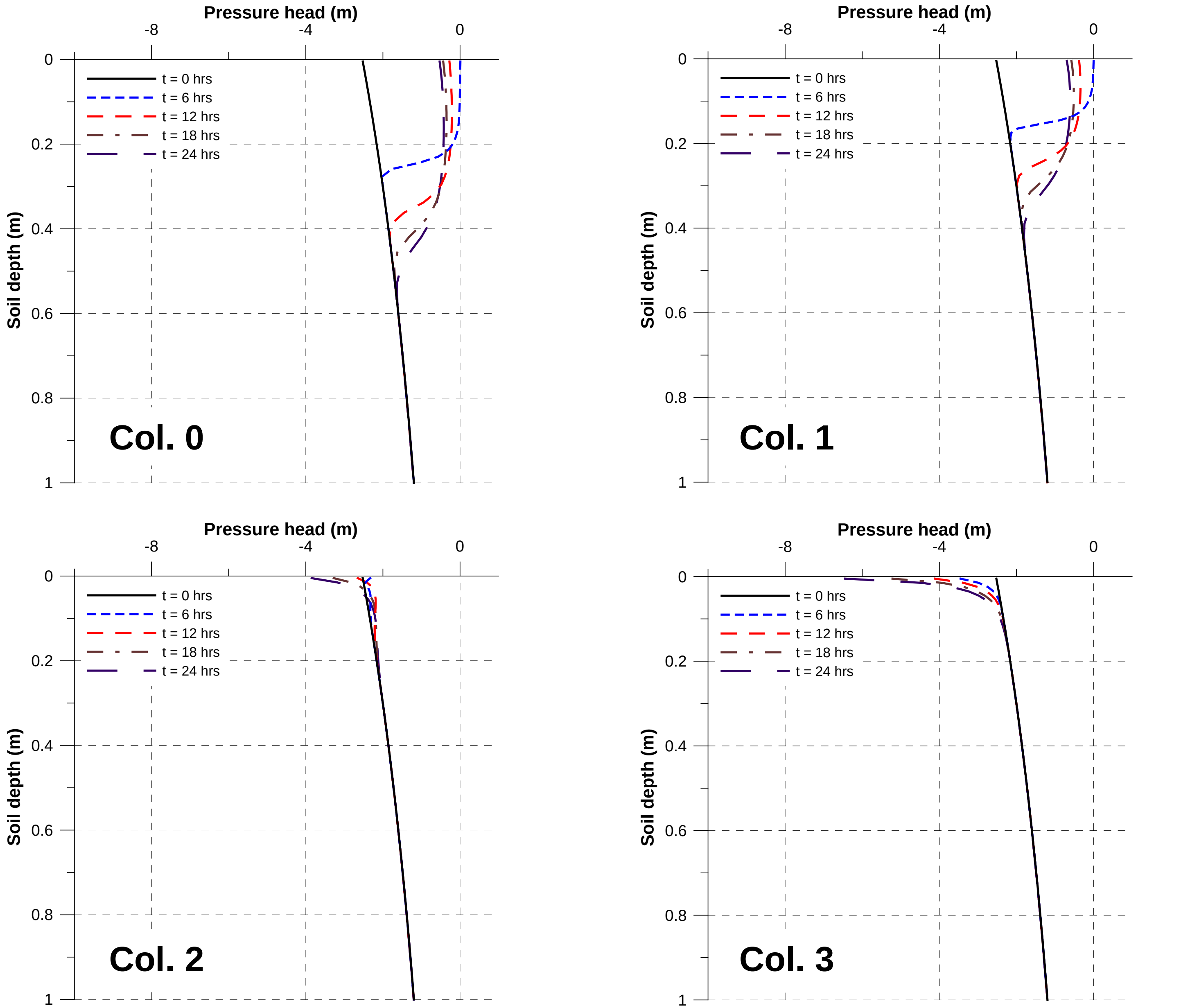
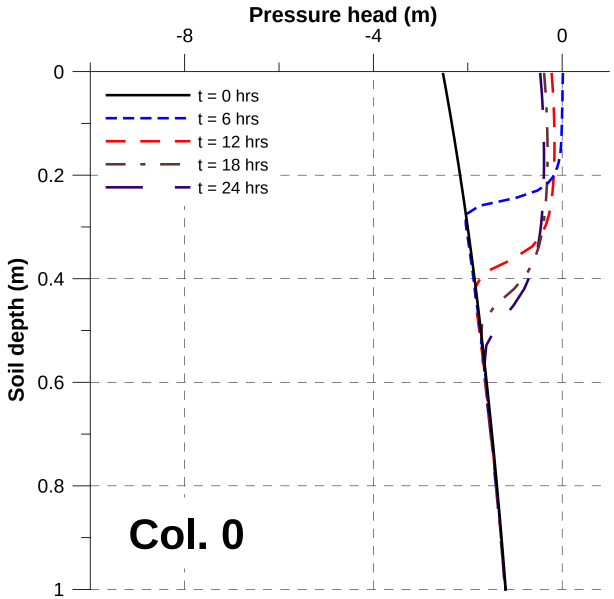


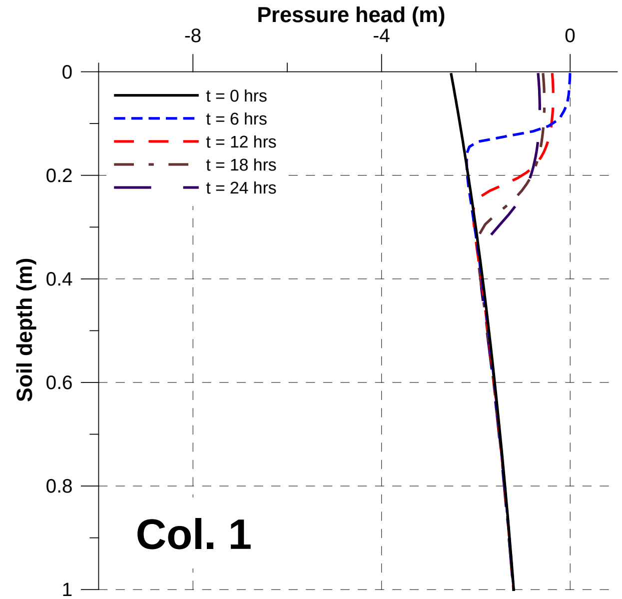
BORDER
Irrigation
(No Plant)



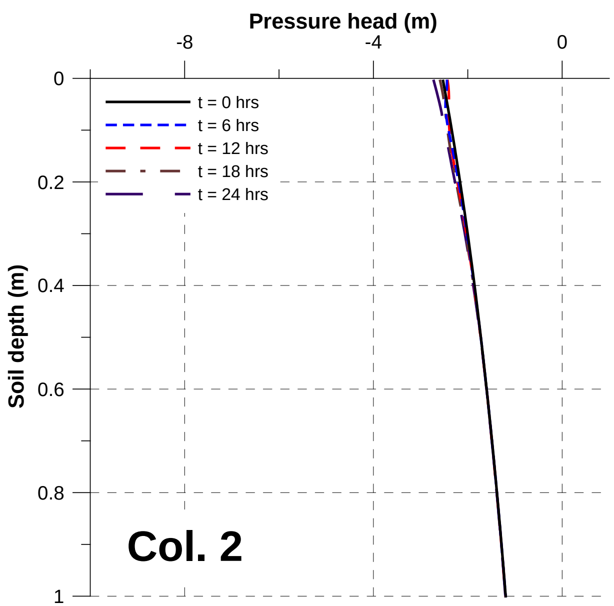
BORDER Irrigation (Plant)

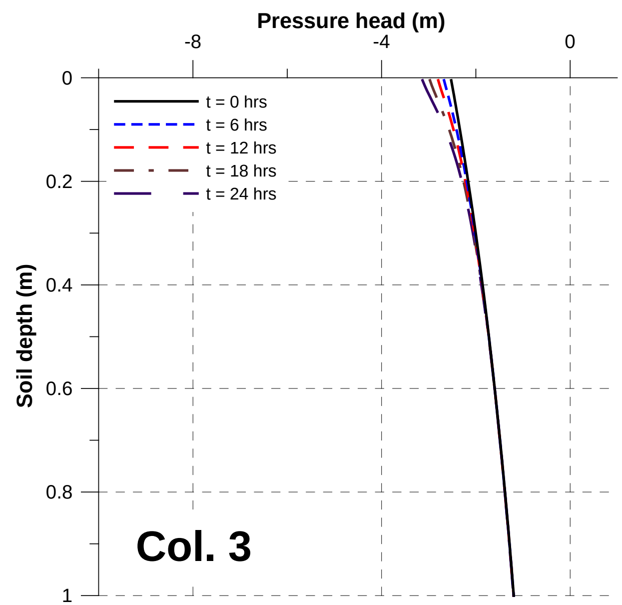
Column 0, 1:
Corn, *LAI* = 3.0



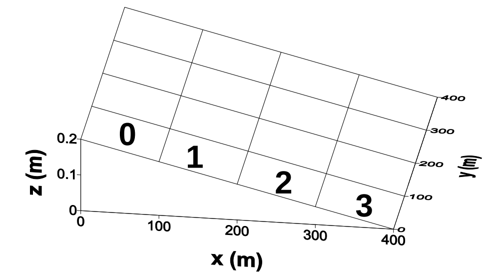


Column 2, 3:
Hay, *LAI* = 5.0

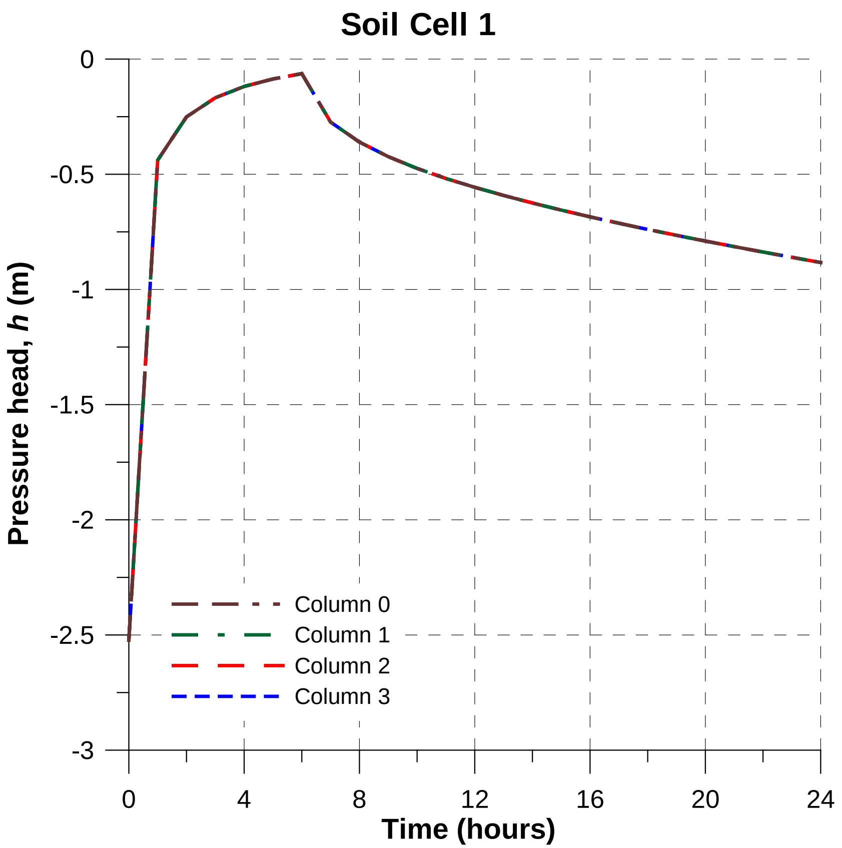




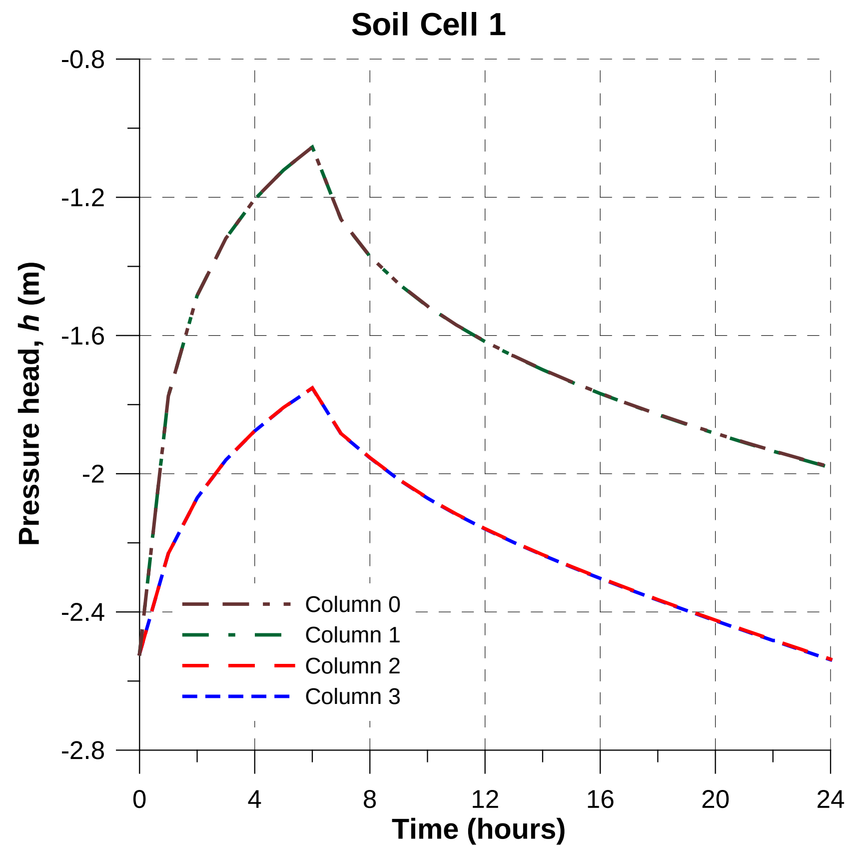
Daily Simulations
SPRINKLER IRRIGATION



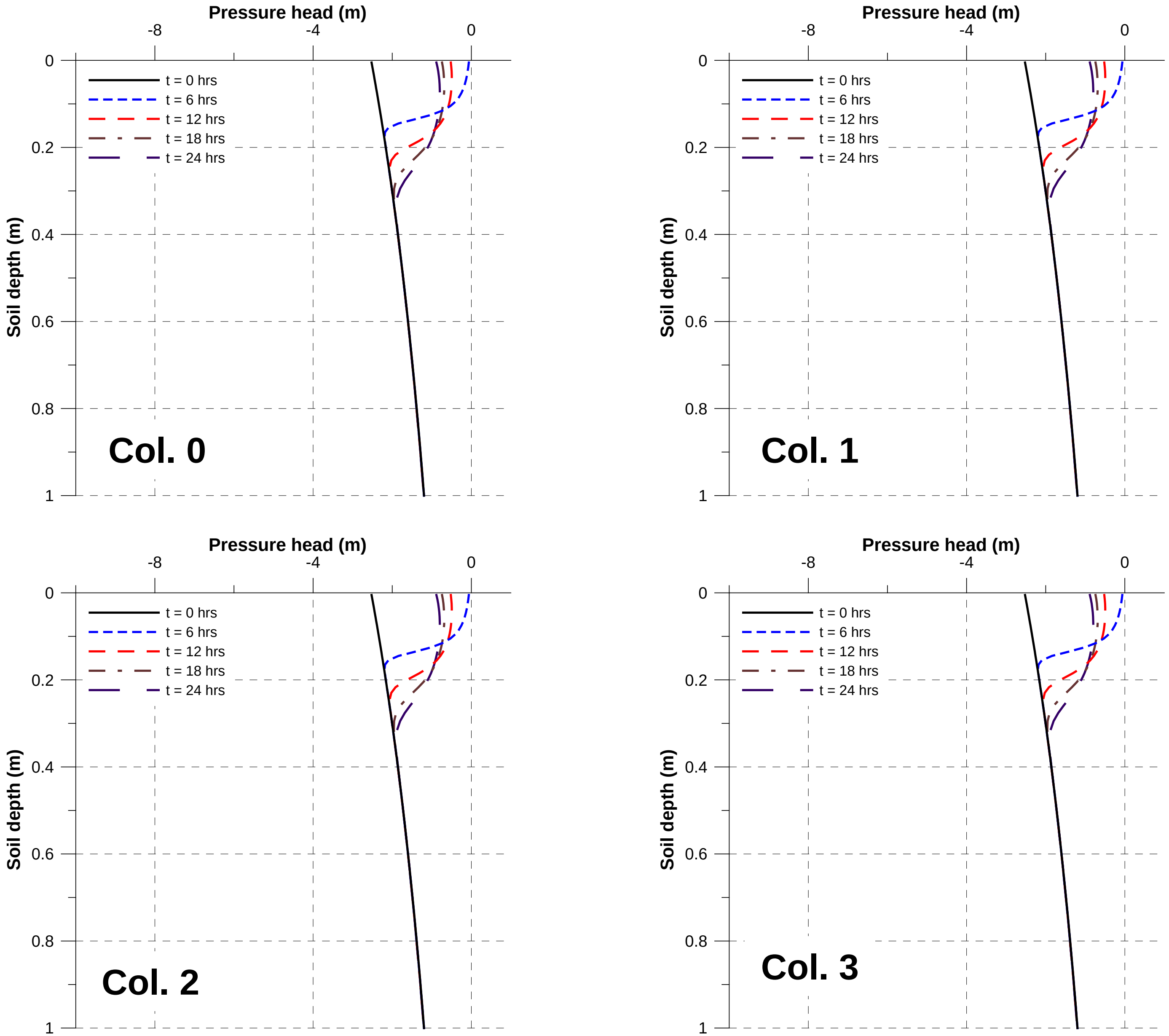
NO PLANT



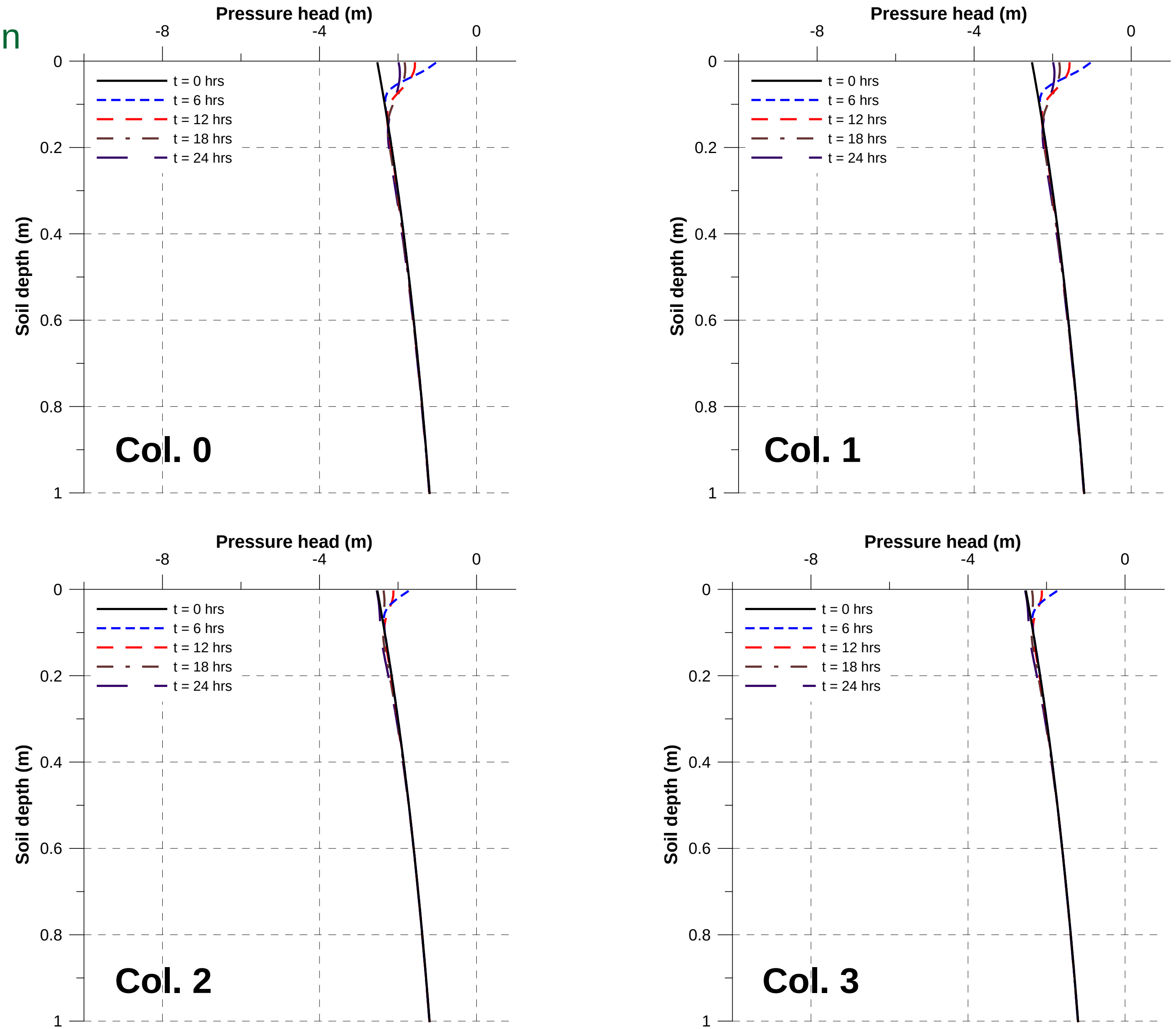
Column 0, 1: Corn, *LAI* = 3.0
Column 2, 3: Hay, *LAI* = 5.0



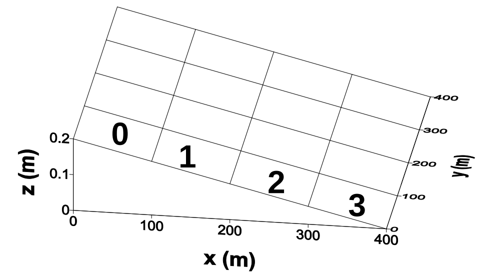
Daily Simulation SPRINKLER Irrigation (No Plant)

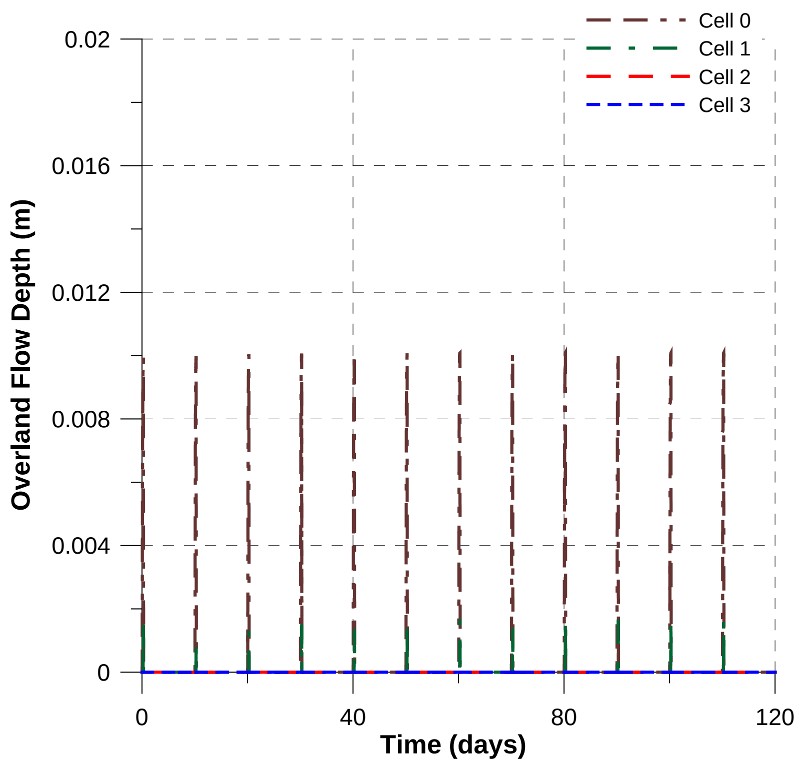


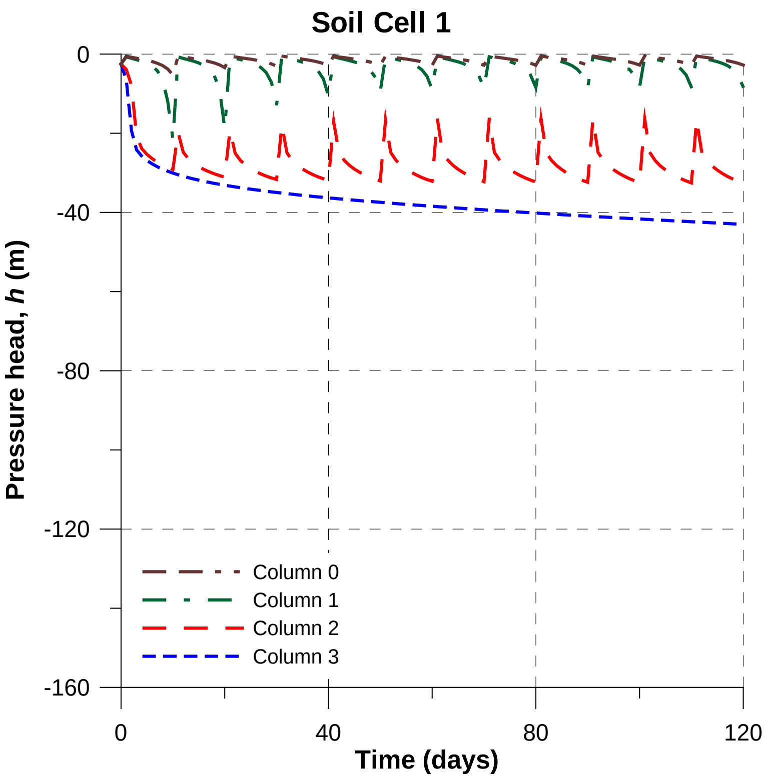
Daily Simulation SPRINKLER Irrigation (Plant)



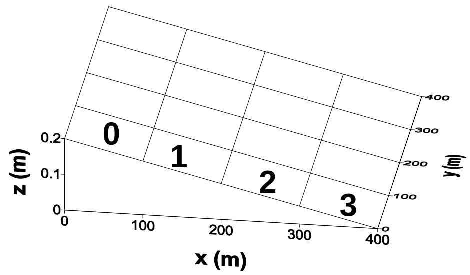
Seasonal Simulations
BORDER Irrigation (No Plant)

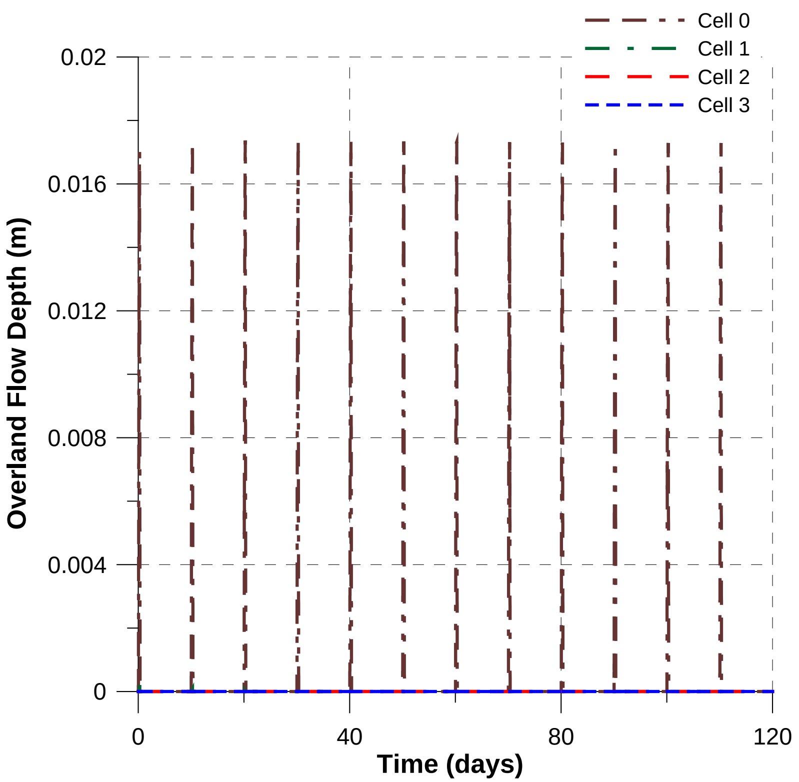


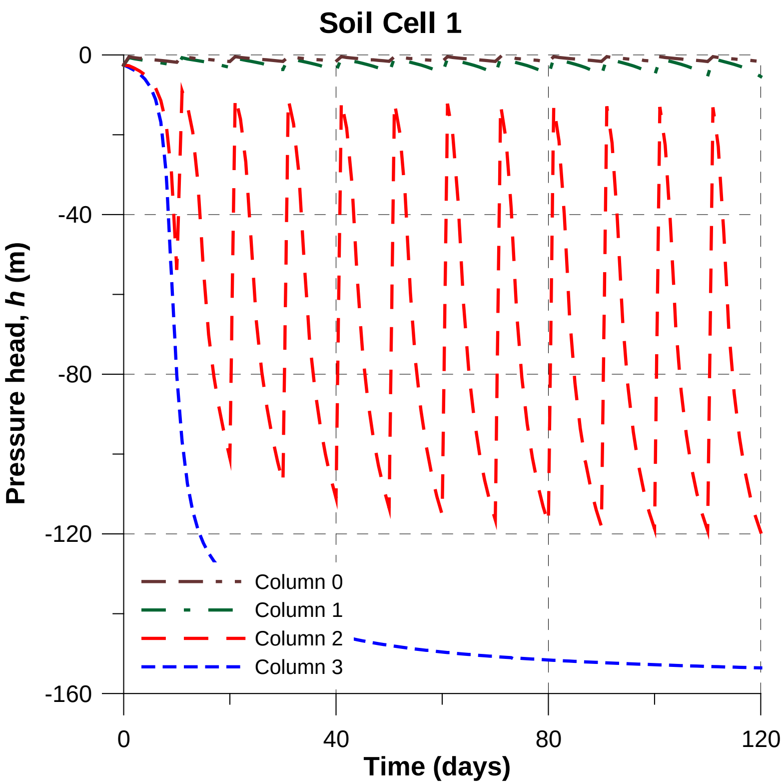




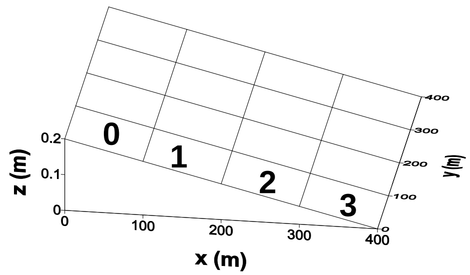
Seasonal Simulations
BORDER Irrigation (Const. Plant)

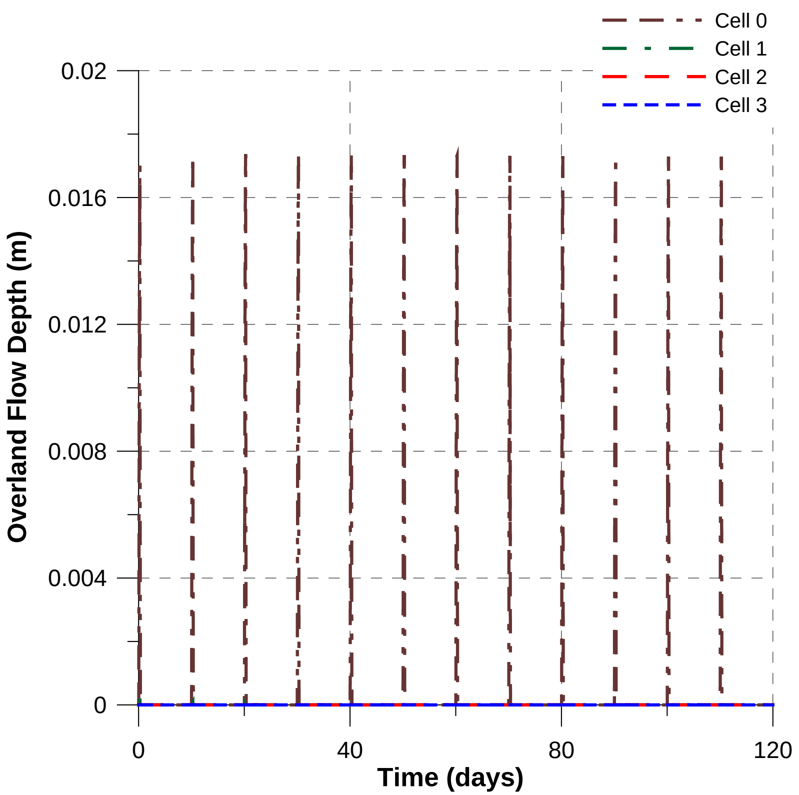


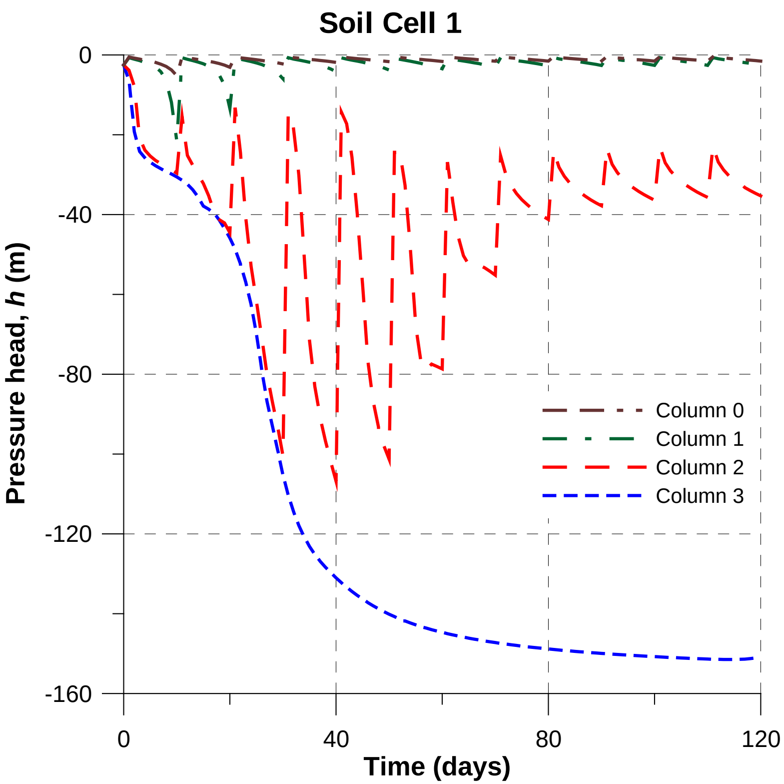




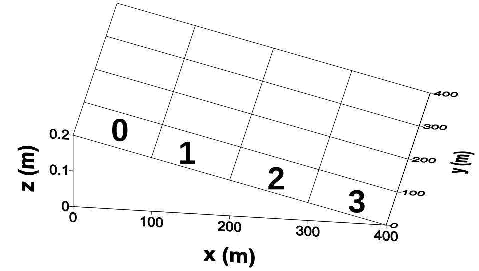
Seasonal Simulations BORDER Irrigation (Plant)



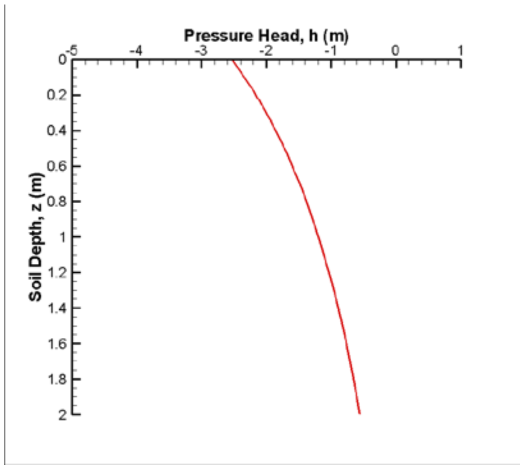




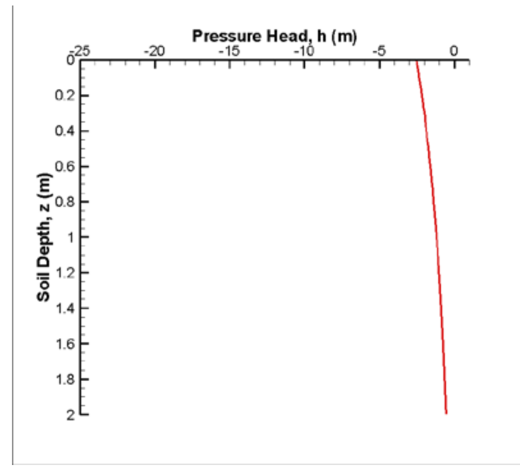
Border Irrigation (No Plant)



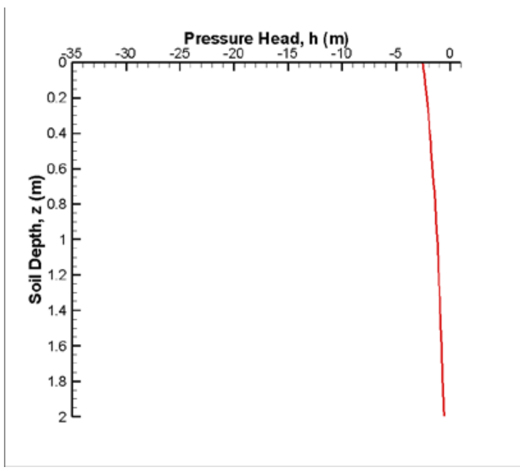
Col. 0



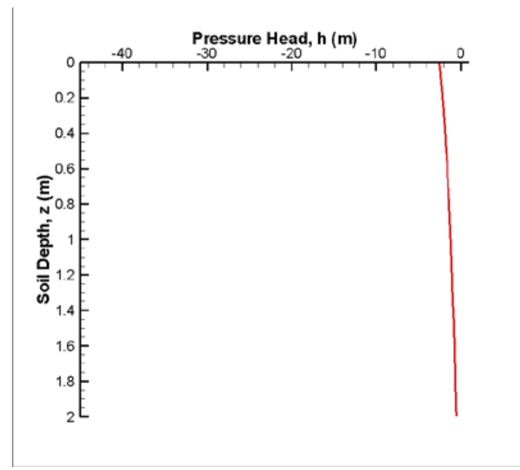
Col. 1



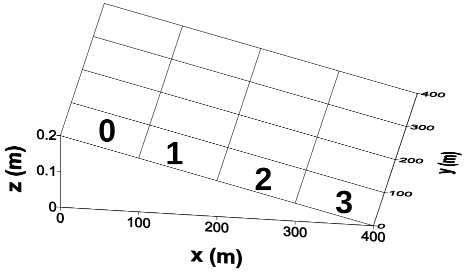
Col. 2

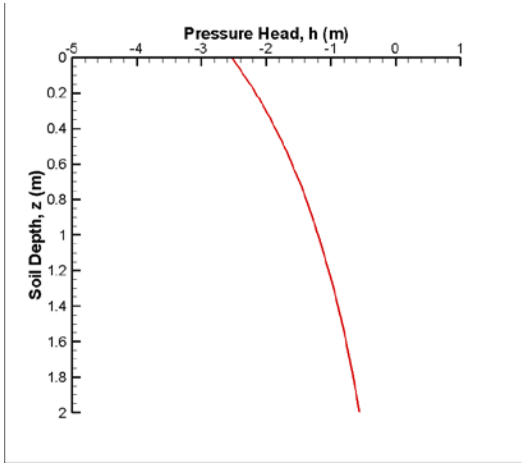


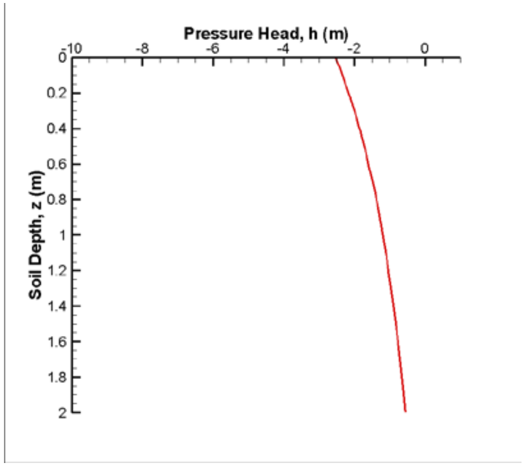
Col. 3

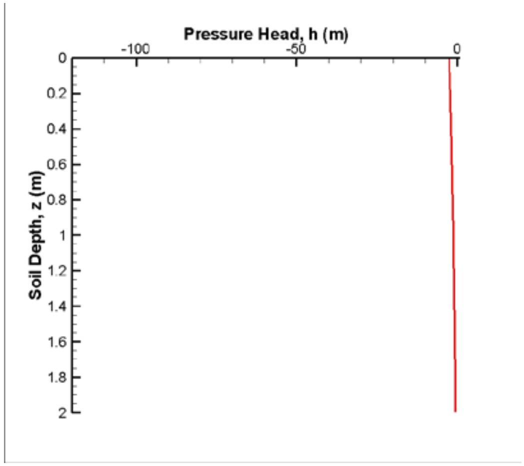


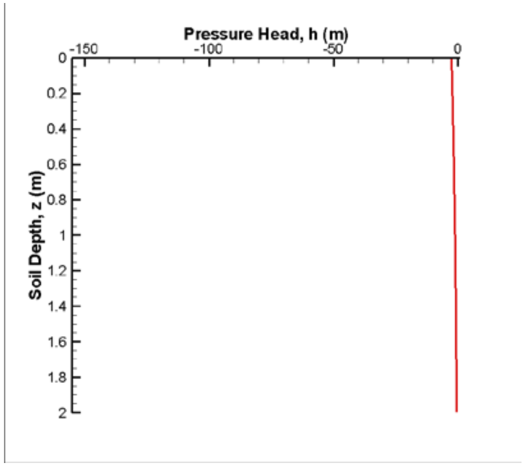
Border Irrigation (Const. Plant)



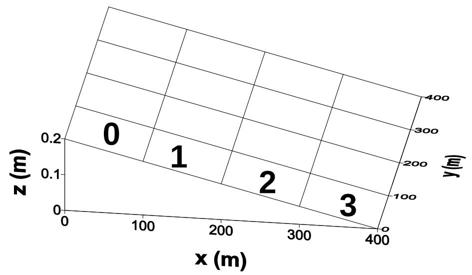


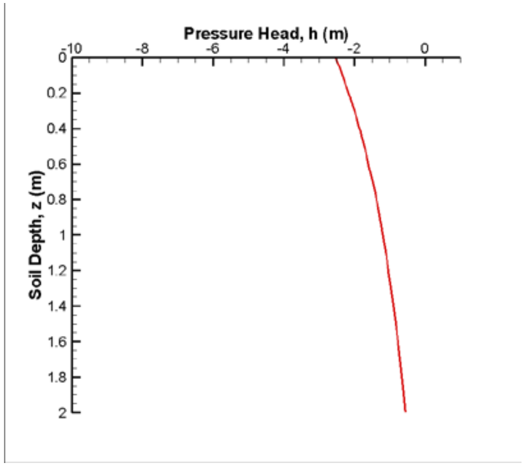


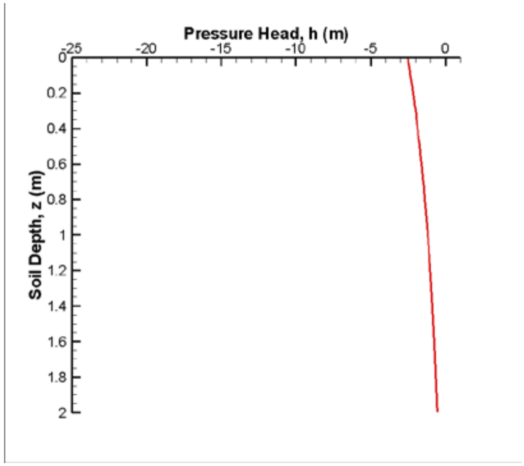


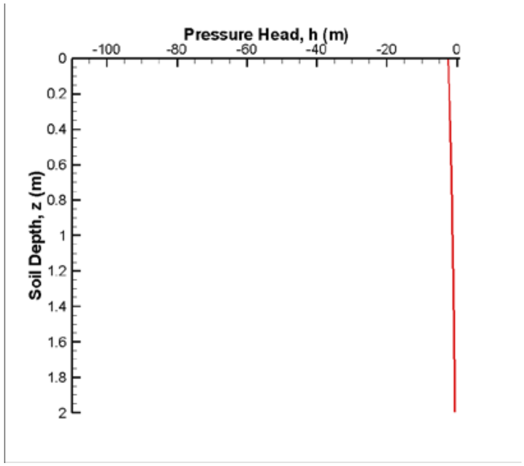


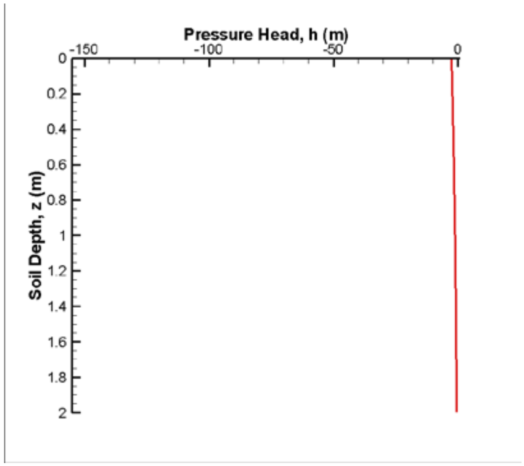
Border Irrigation (Plant)



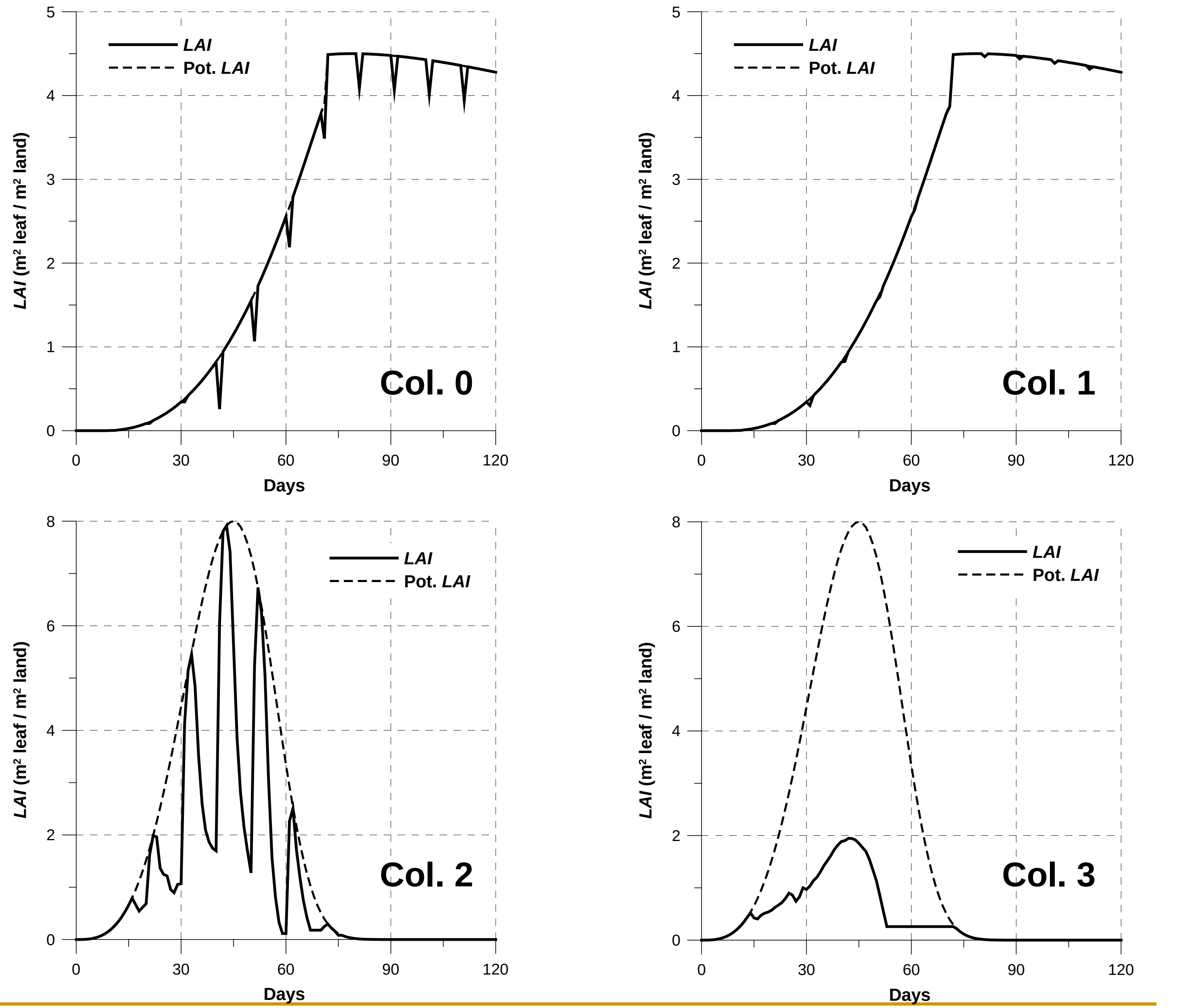




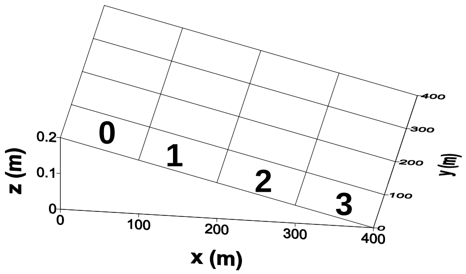




BORDER Irrigation



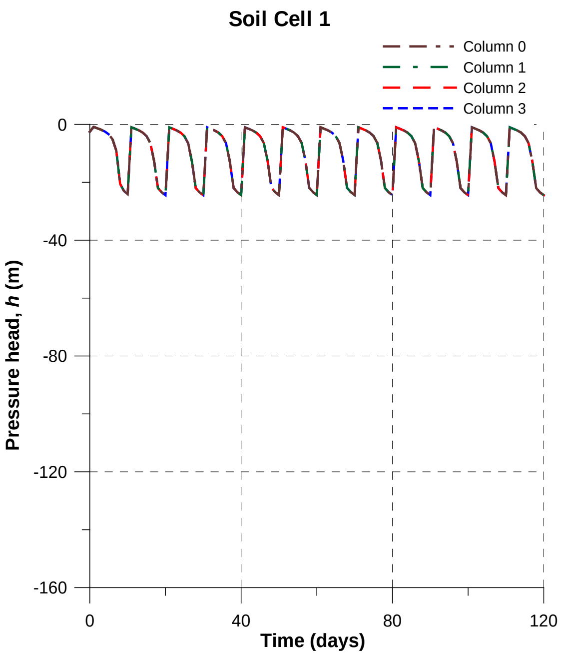
Seasonal Simulations
Sprinkler Irrigation (No Plant)

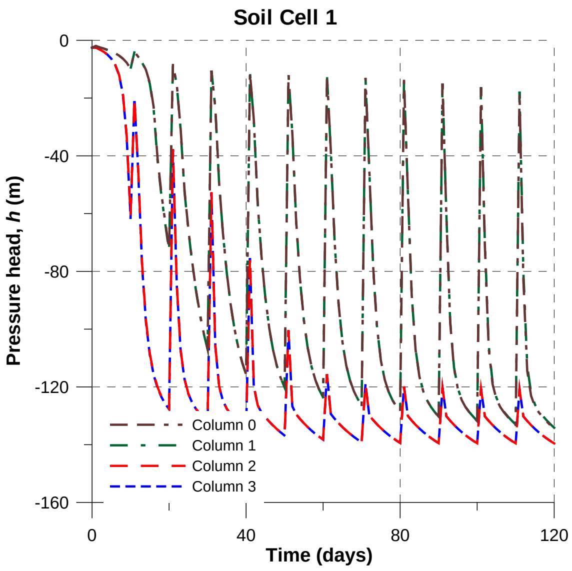


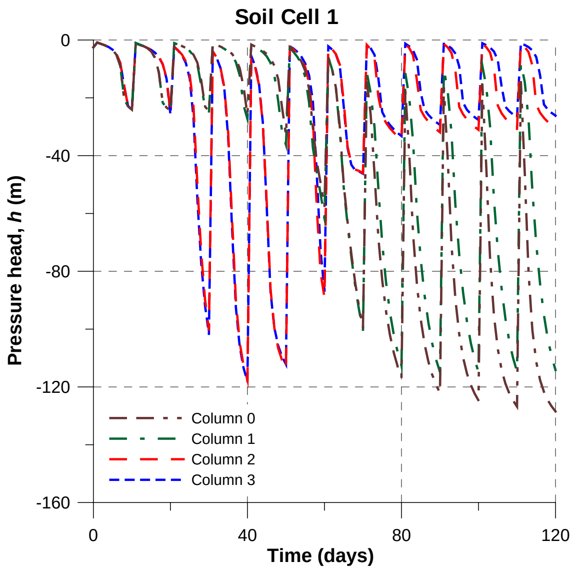
No Plant

Const. Plant

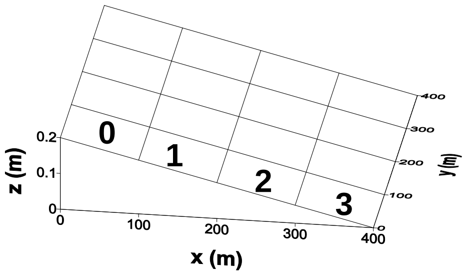
Plant

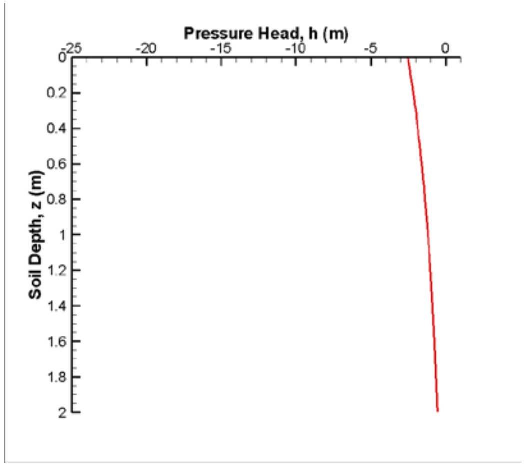


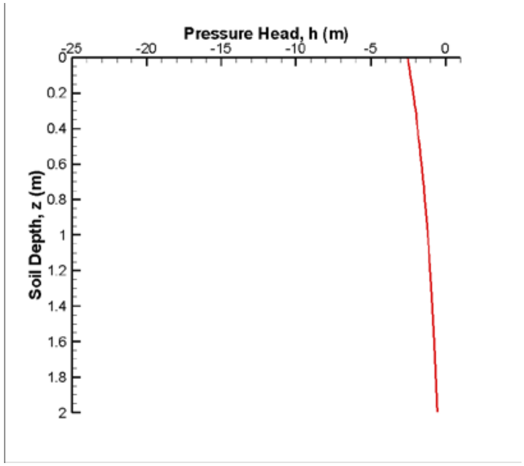


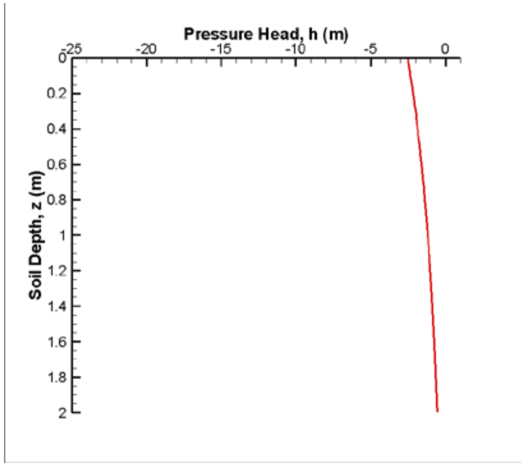


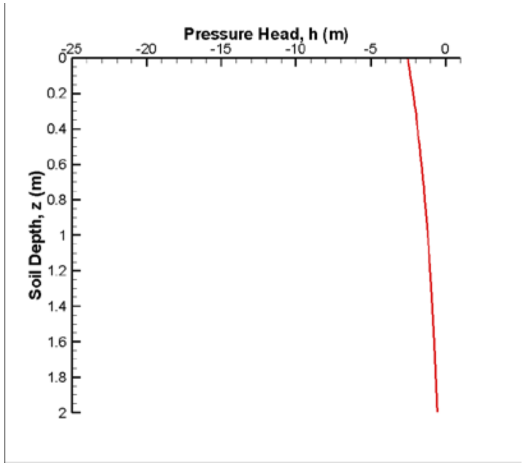
Sprinkler Irrigation (No Plant)



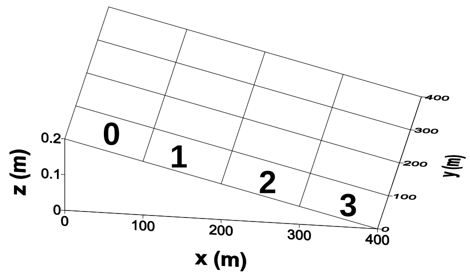


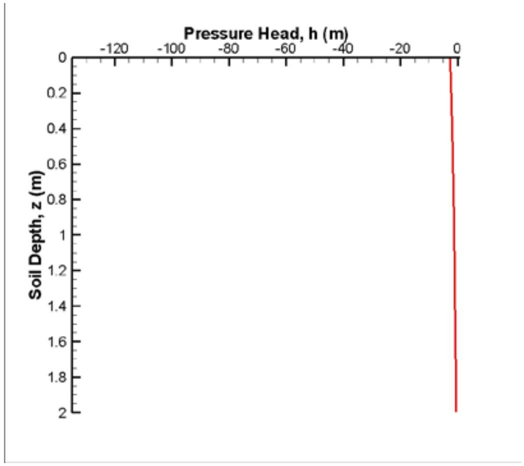


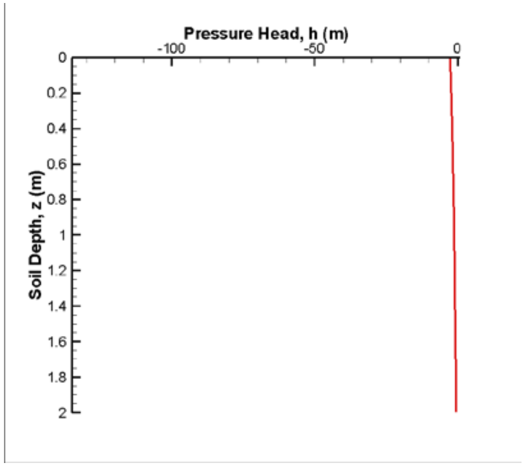


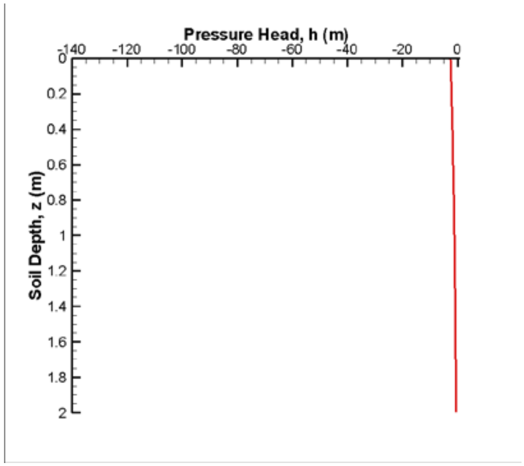


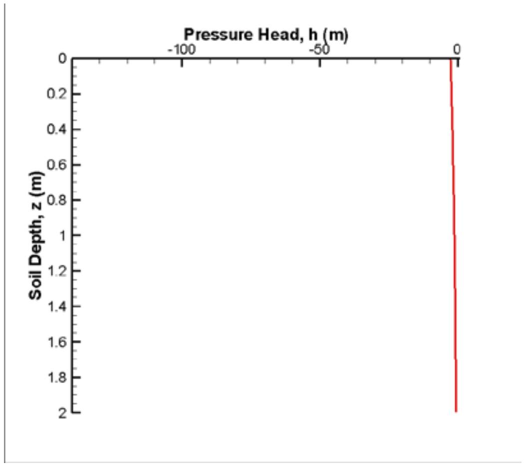
Sprinkler Irrigation (Const. Plant)



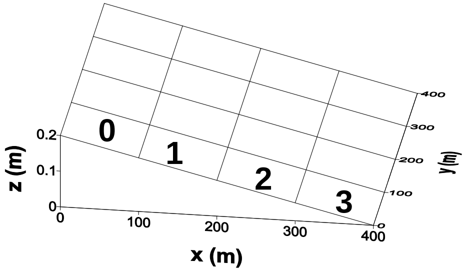


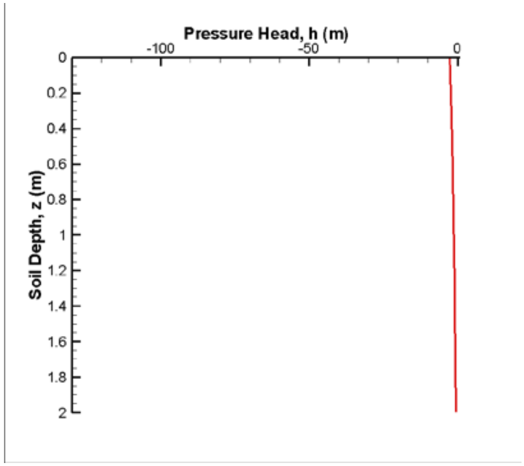


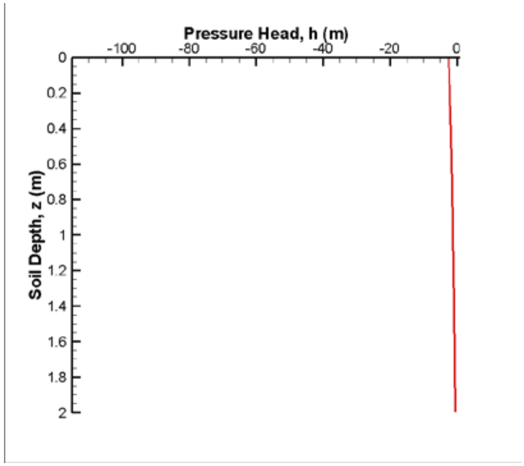


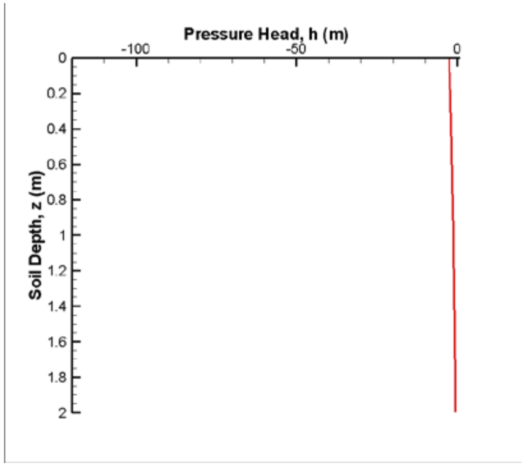


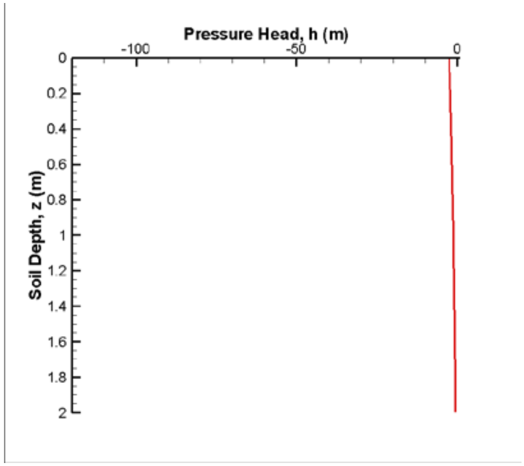
Sprinkler Irrigation (Plant)



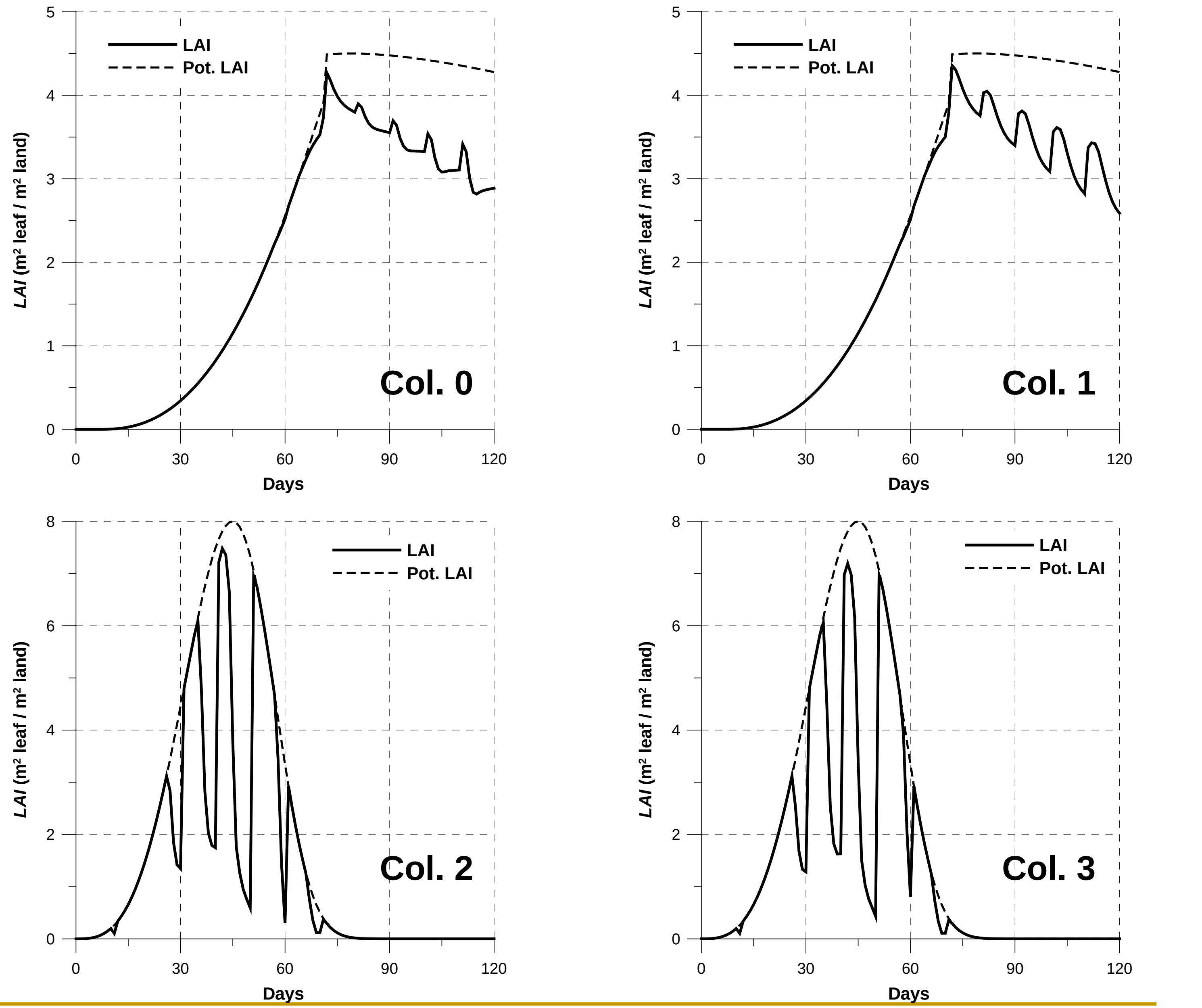




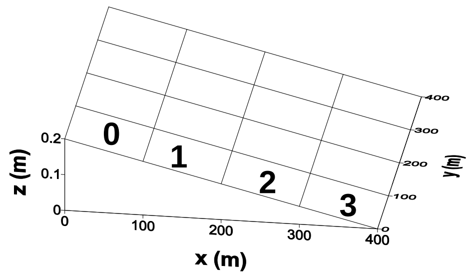


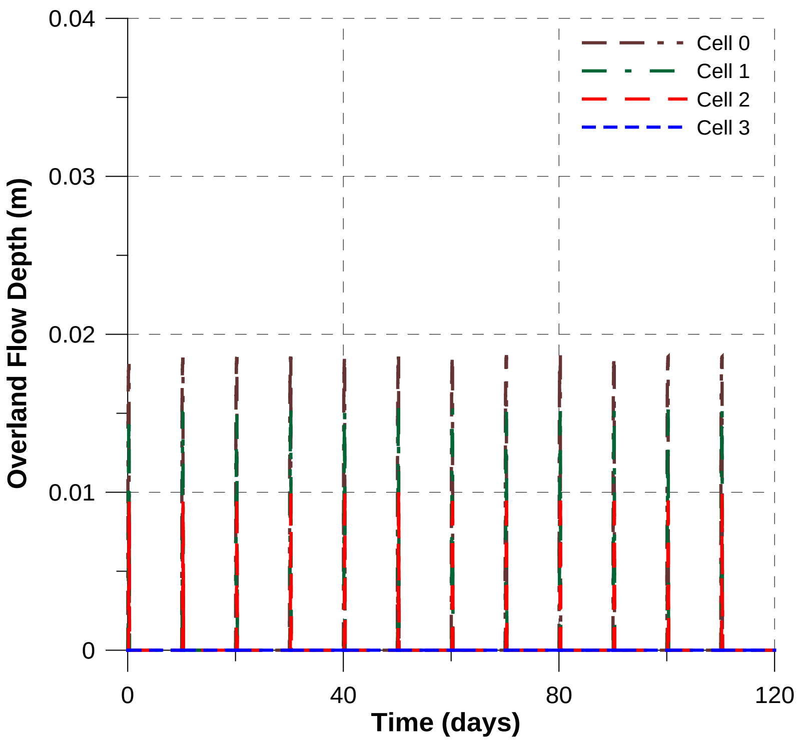


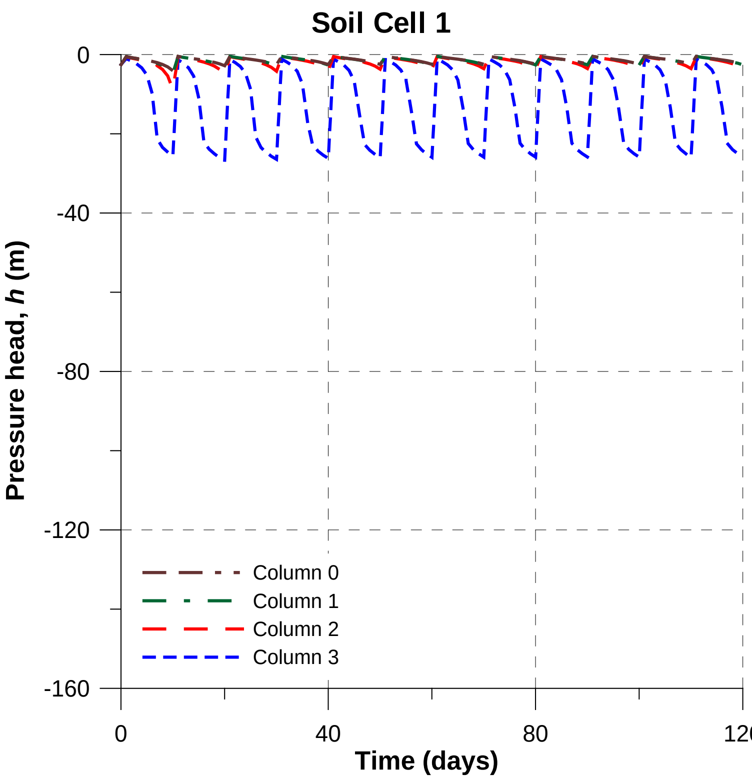
SPRINKLER Irrigation



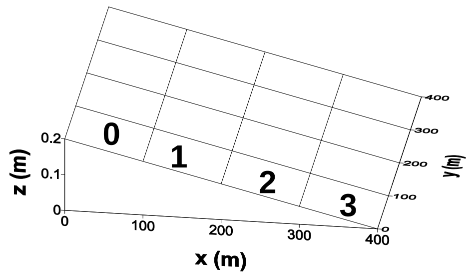
2× Enhanced Irrigation BORDER (No Plant)

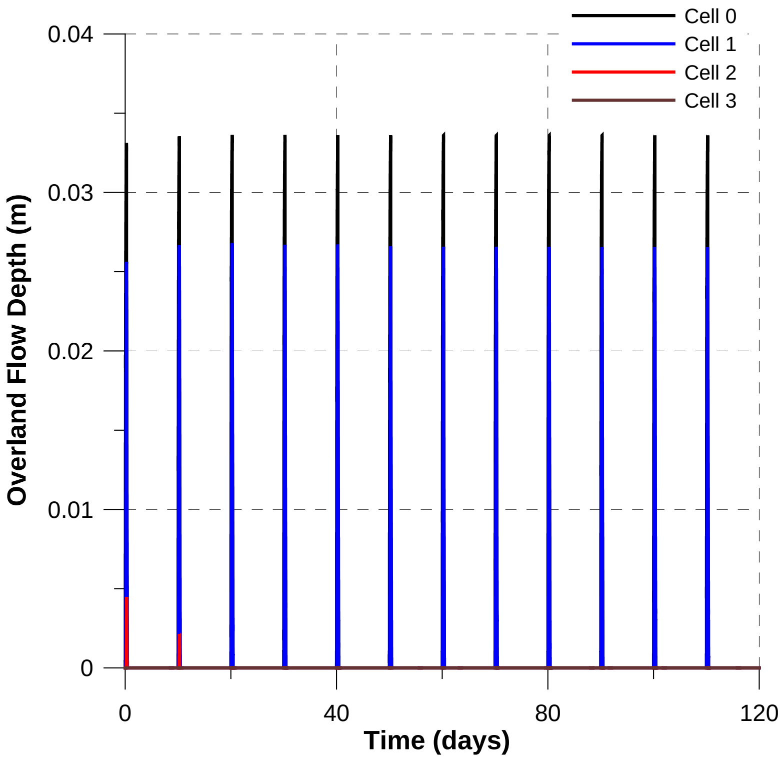


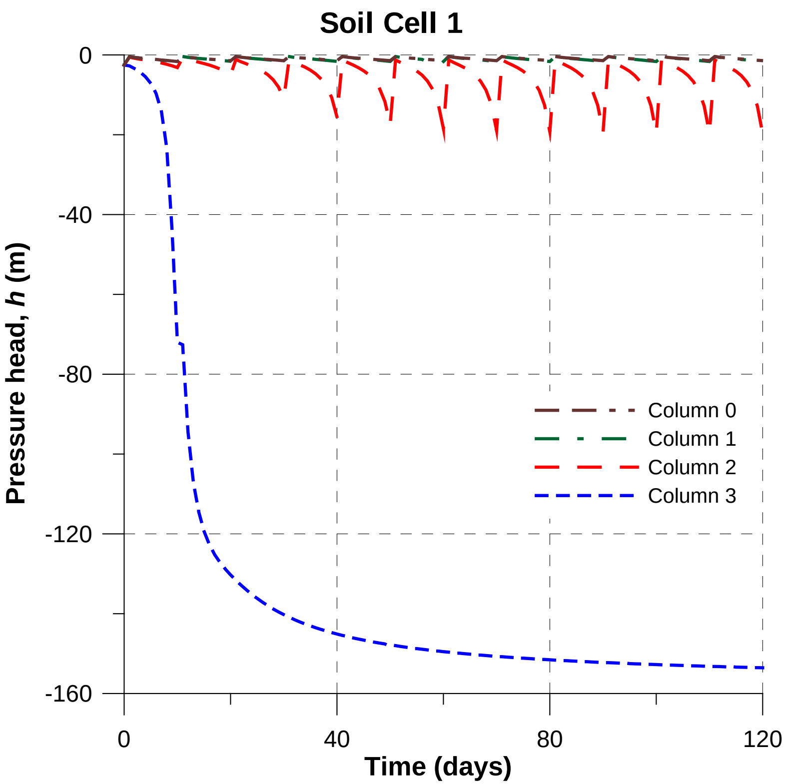




2× Enhanced Irrigation BORDER (Const. Plant)







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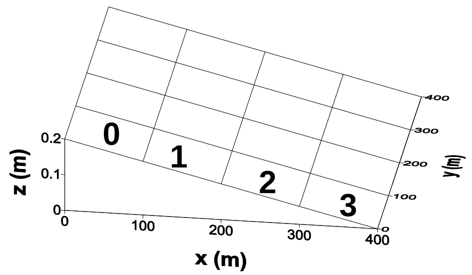

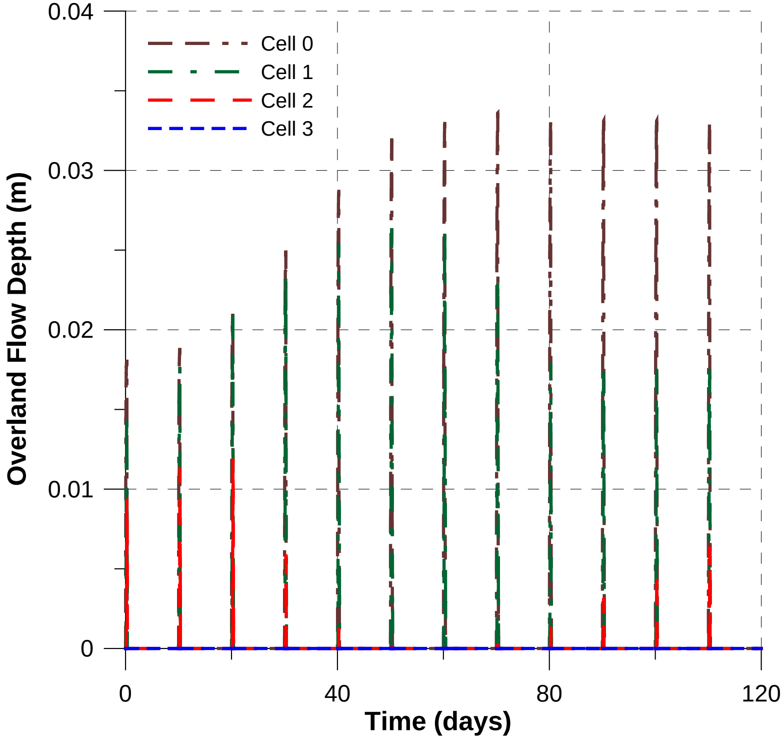

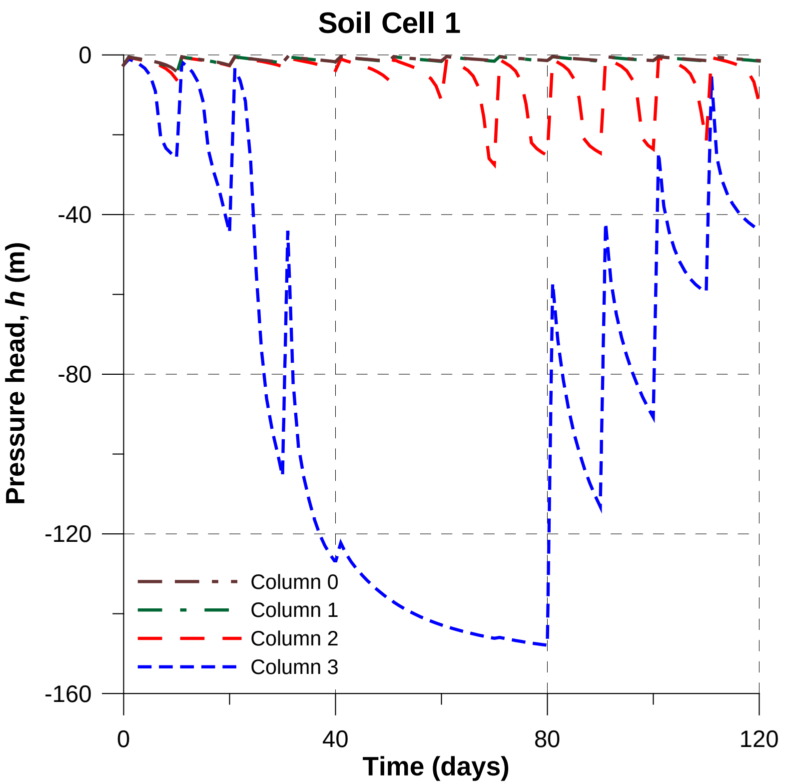

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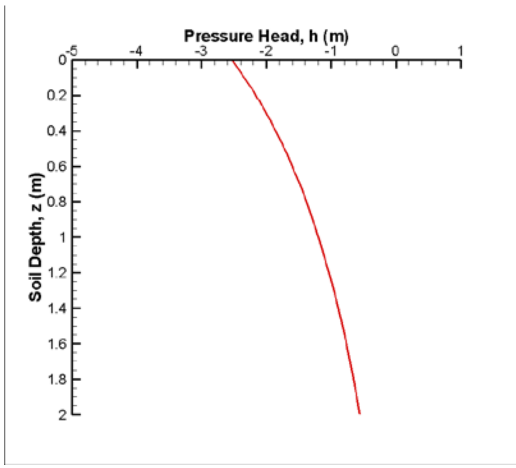

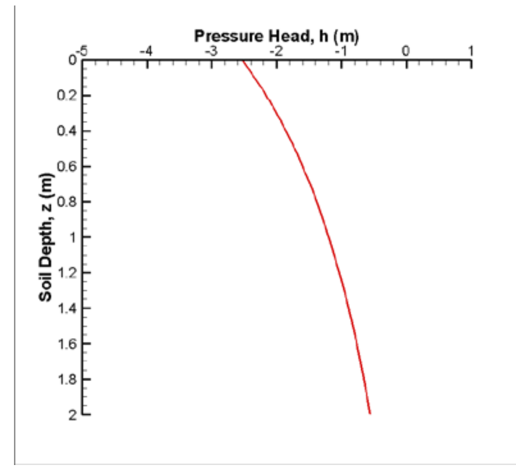

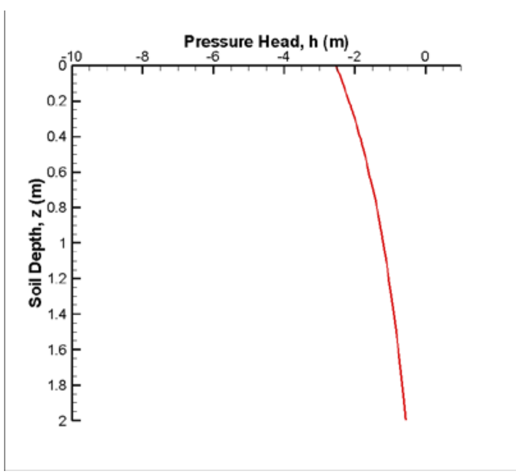

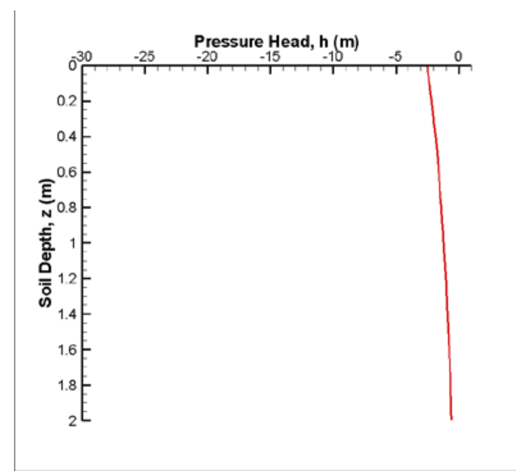

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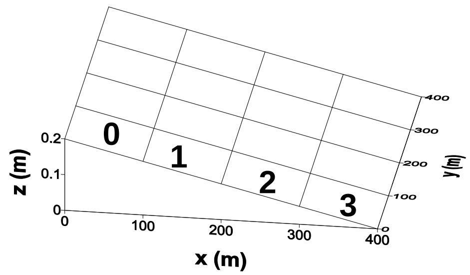

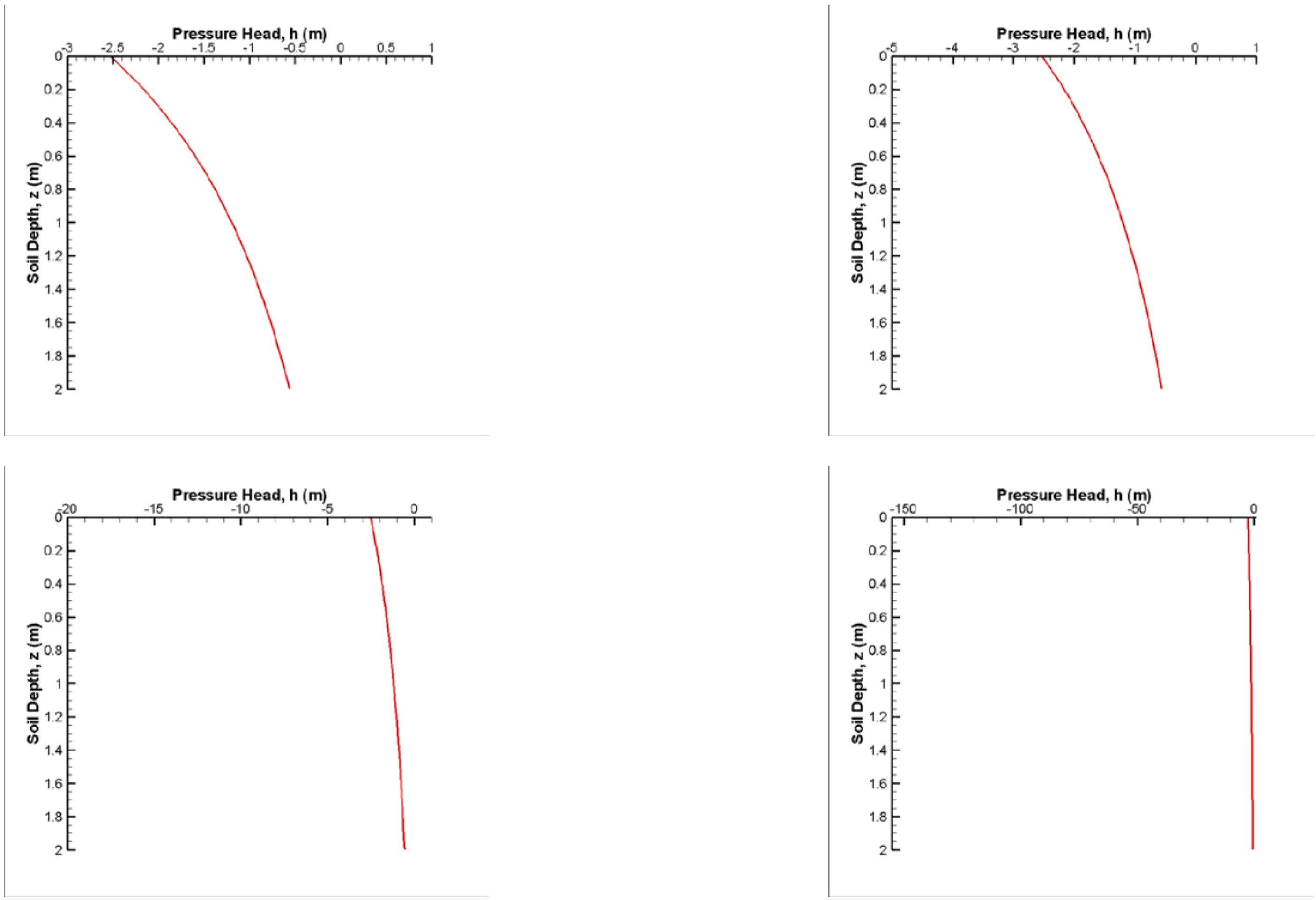

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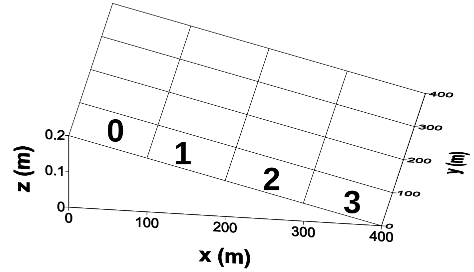
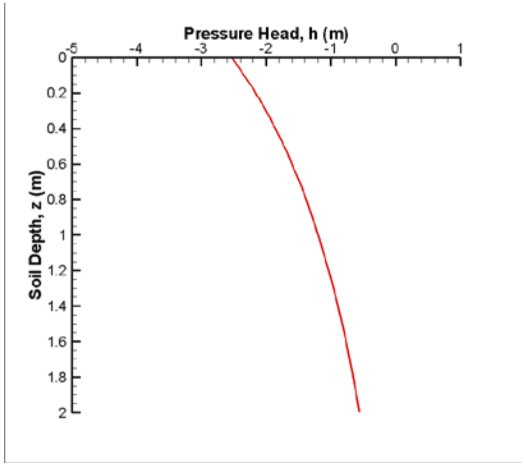
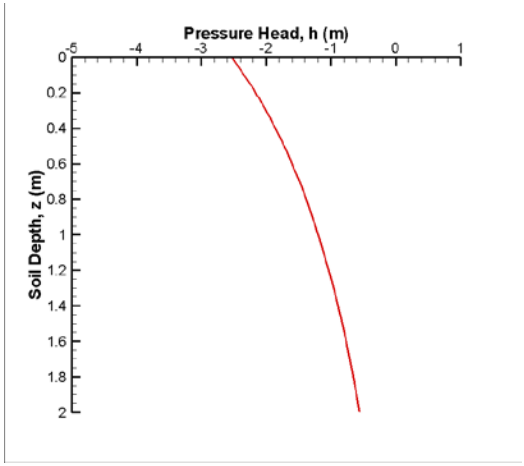
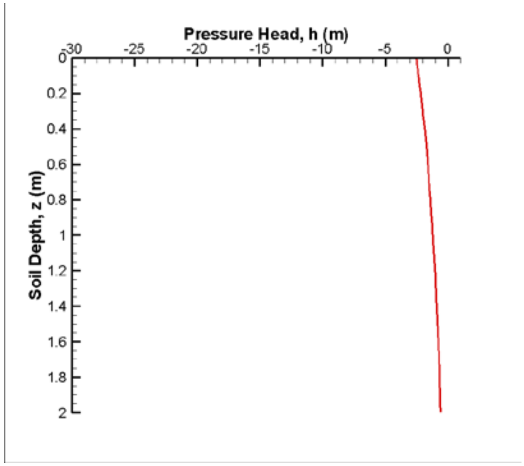
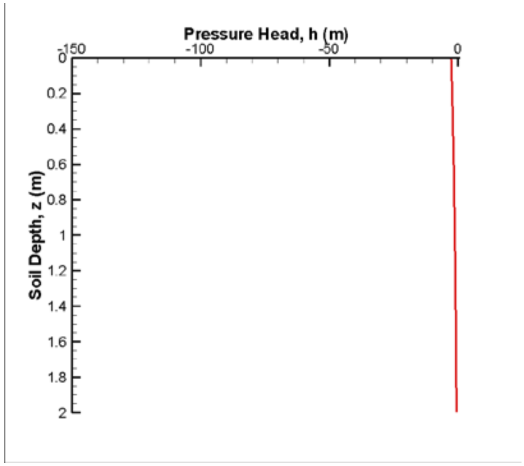


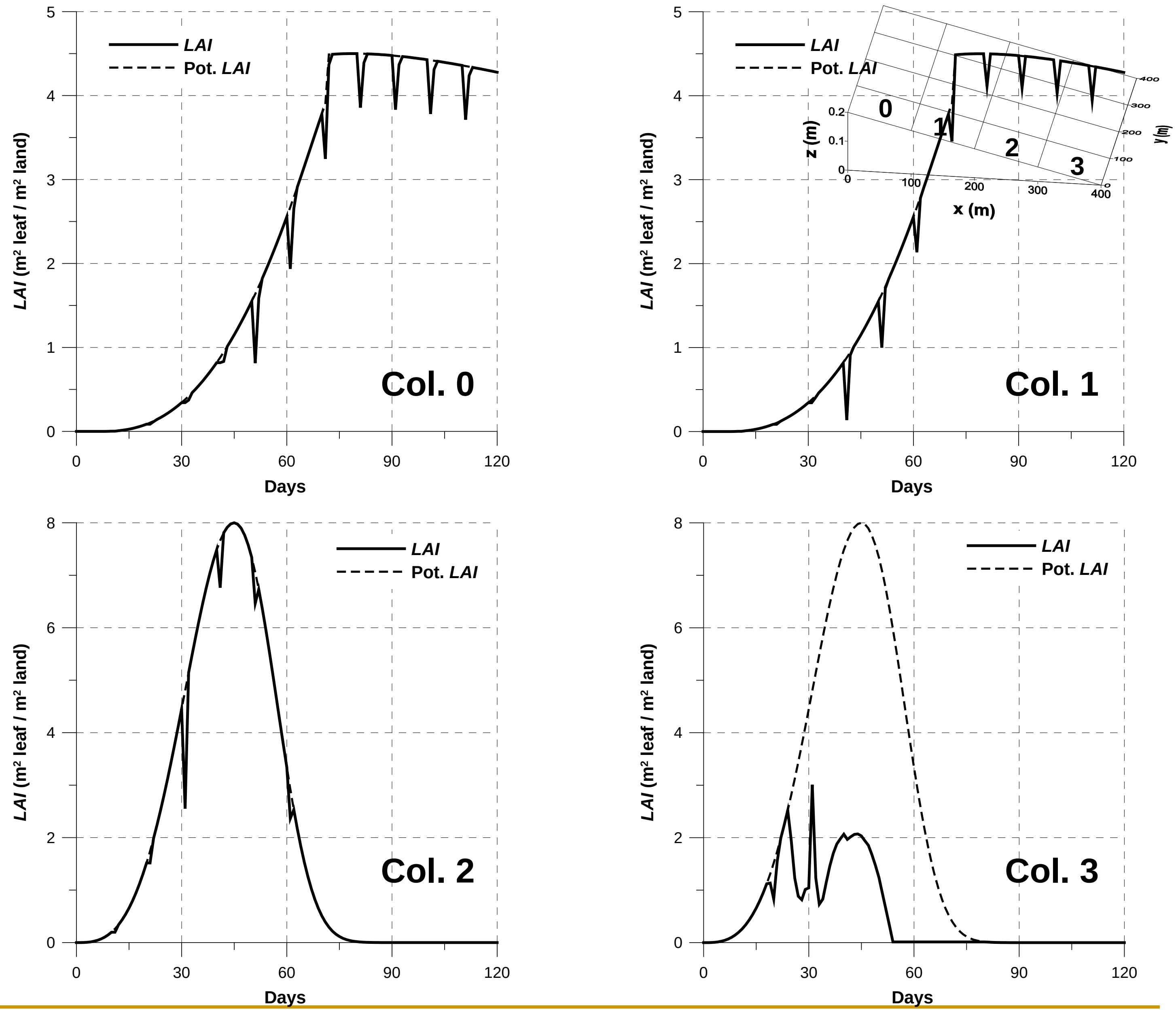




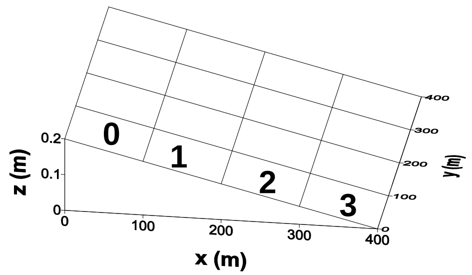




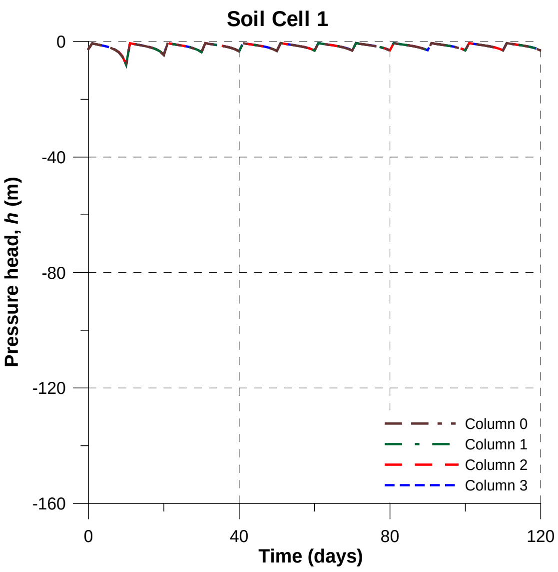
2× BORDER Irrigation



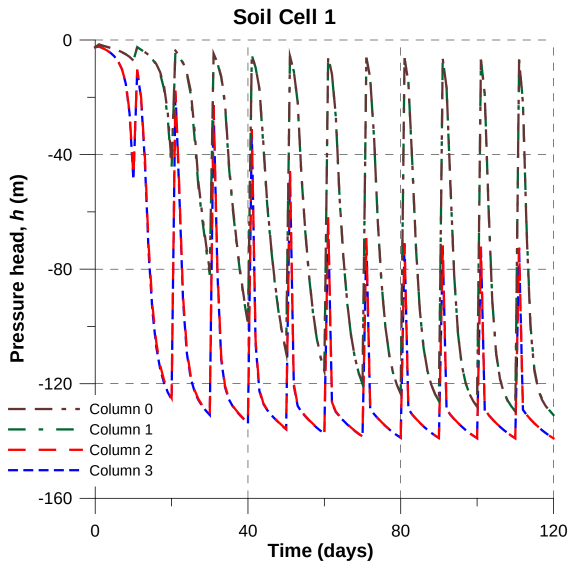
2× Enhanced Irrigation SPRINKLER



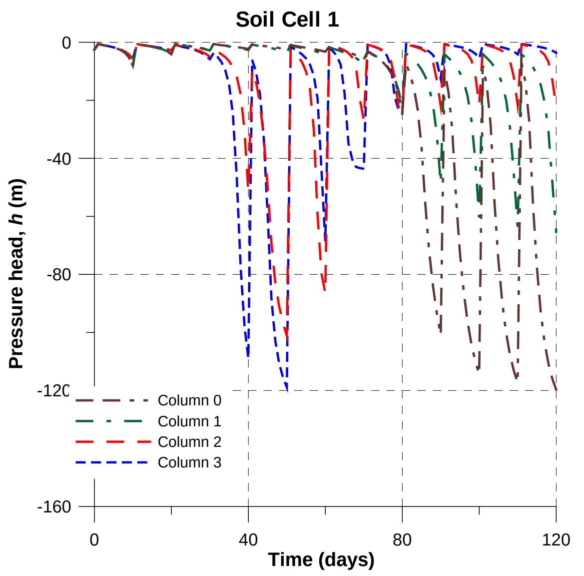
No Plant



Const. Plant



Plant



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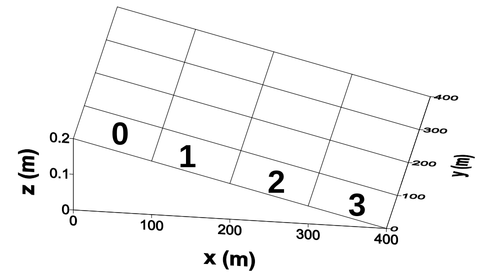

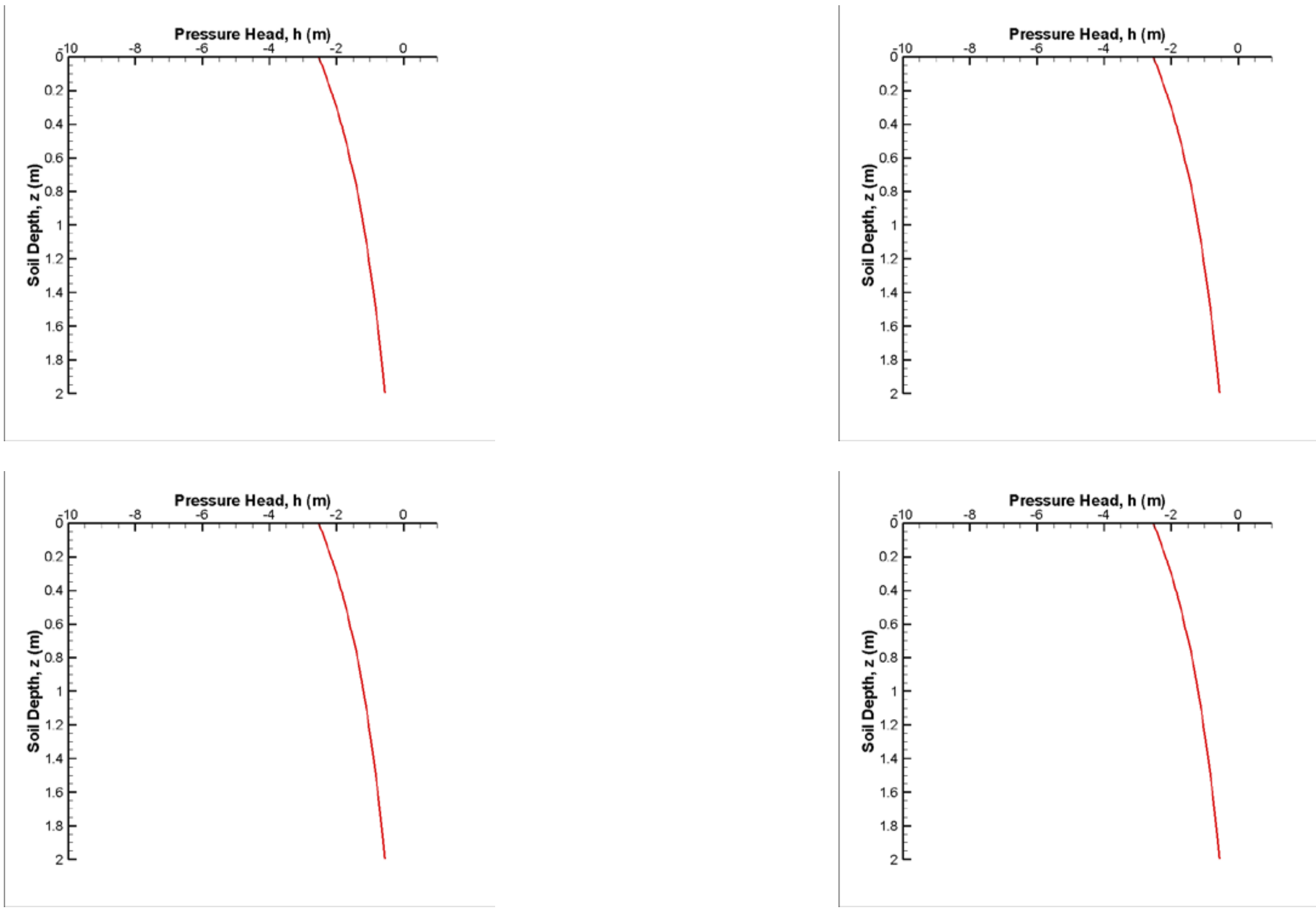

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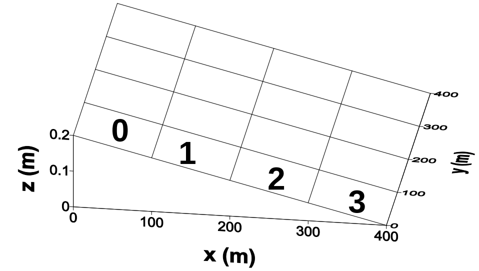
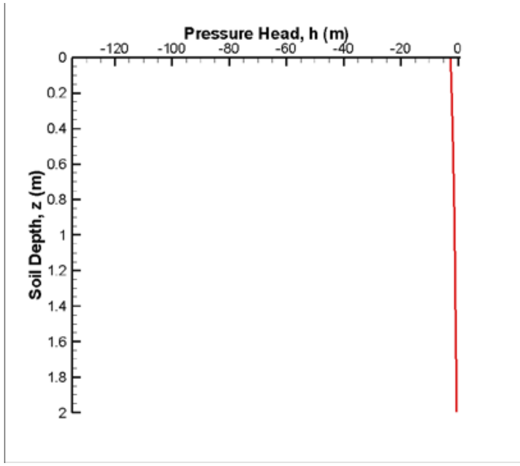
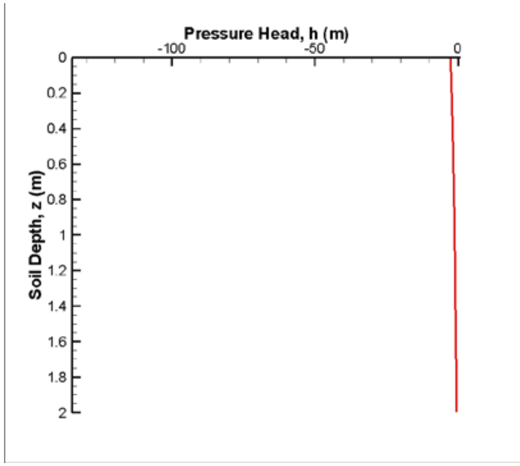
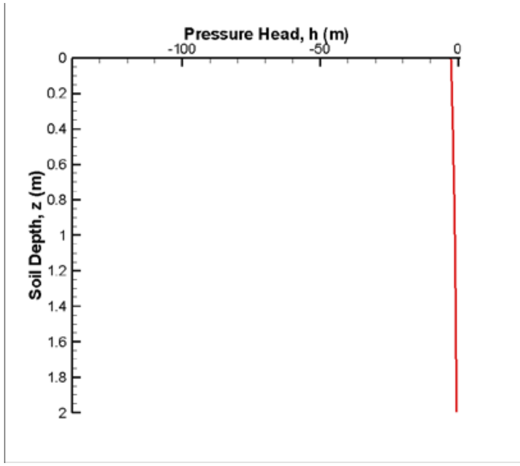
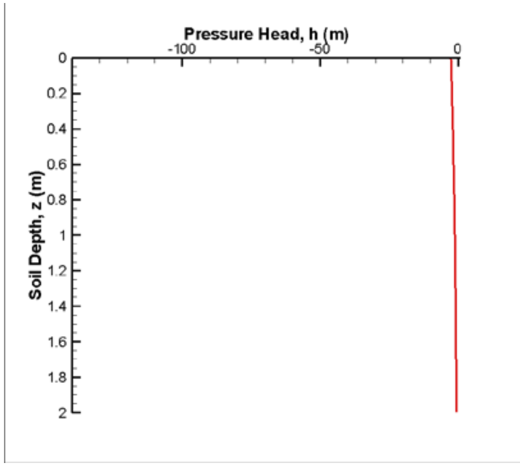


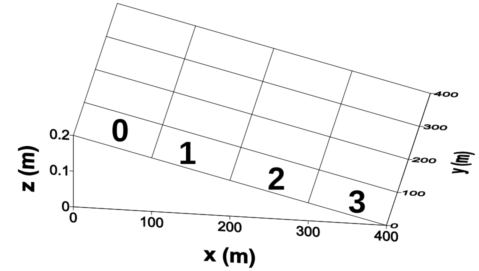


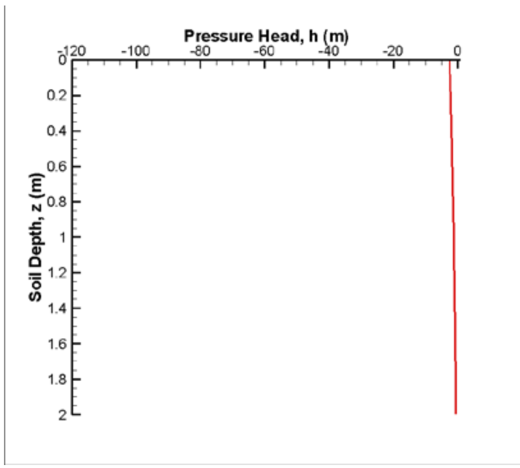


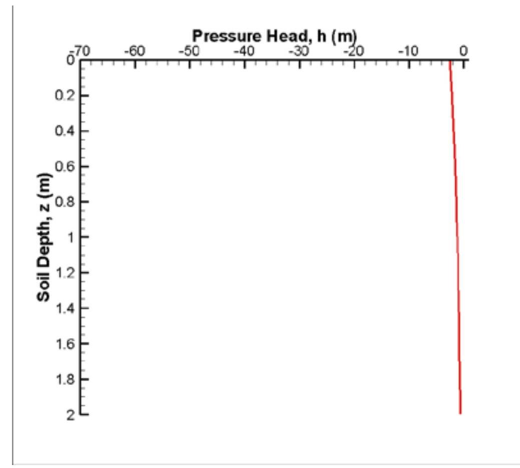


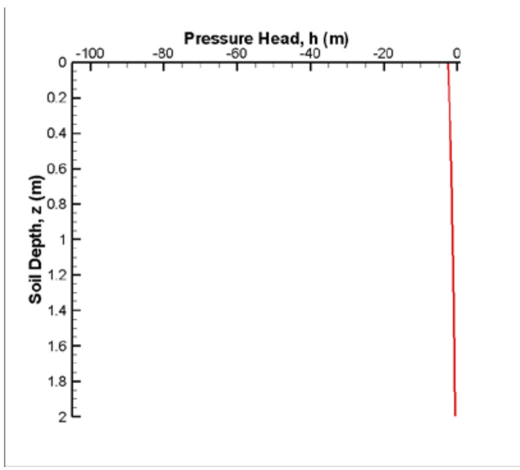


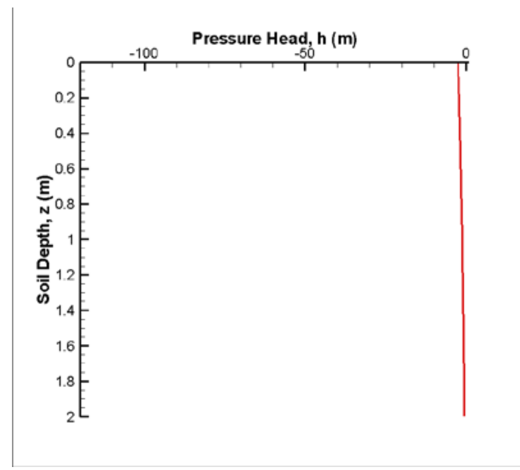
2× Sprinkler Irrigation (Plant)



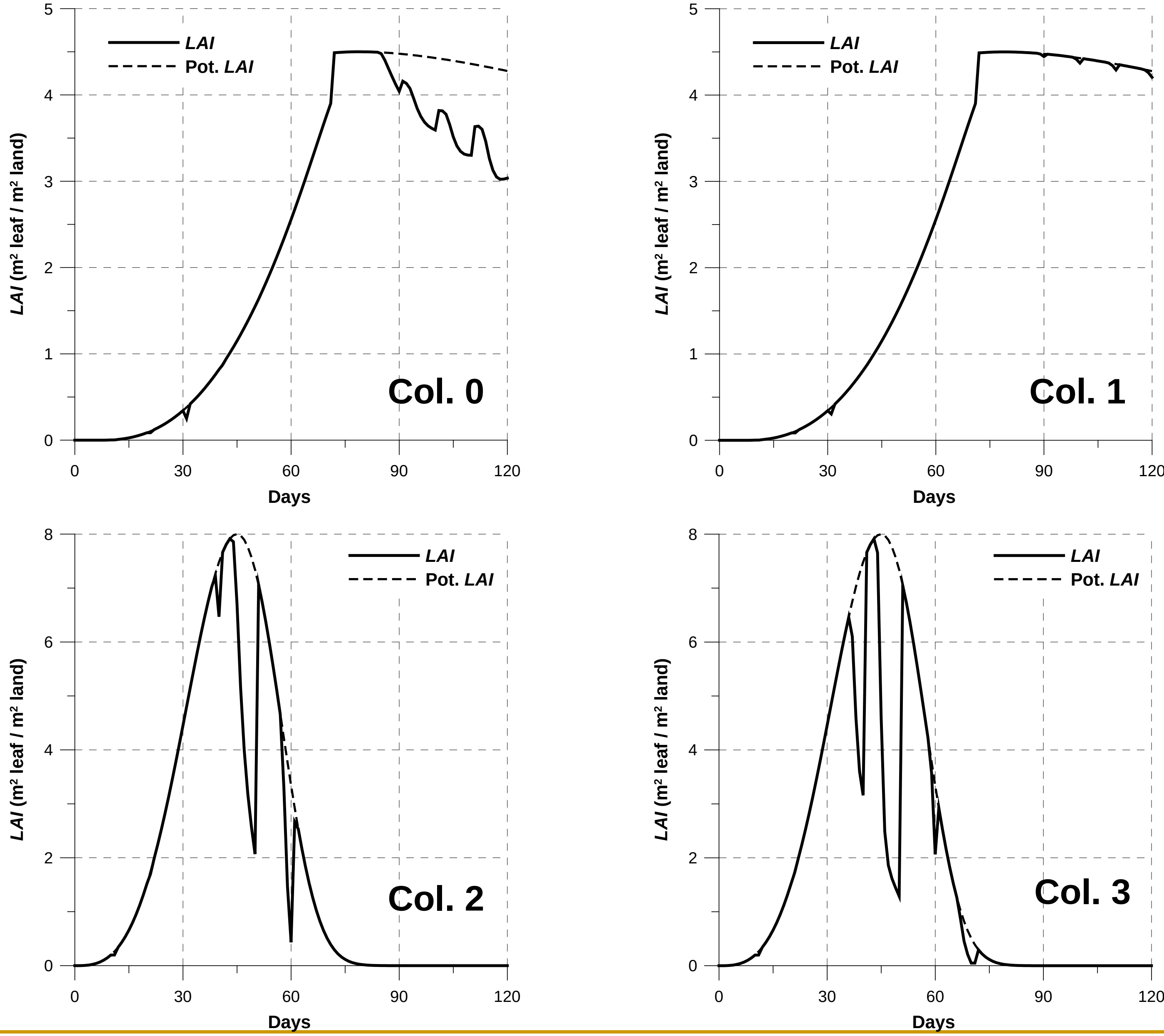








2× SPRINKLER Irrigation



Conclusions

- A model was developed that
  - can describe water flow dynamics on the land surface and within the shallow soil for extended periods of time
  - takes into account the effects of the presence of vegetation on the overall water flow dynamics within the system

- The developed model is
  - able to provide an integrated analysis of water flow dynamics in terrestrial systems.
  - applicable to fields that have heterogeneous vegetation and soil characteristics.

- Model limitations:
  - The model is applicable to fields with relatively mild topography.
  - Groundwater and surface waters are out of the modeling domain.

Thank you…