



Development of an integrated tailings simulation model using System Dynamics and GoldSim

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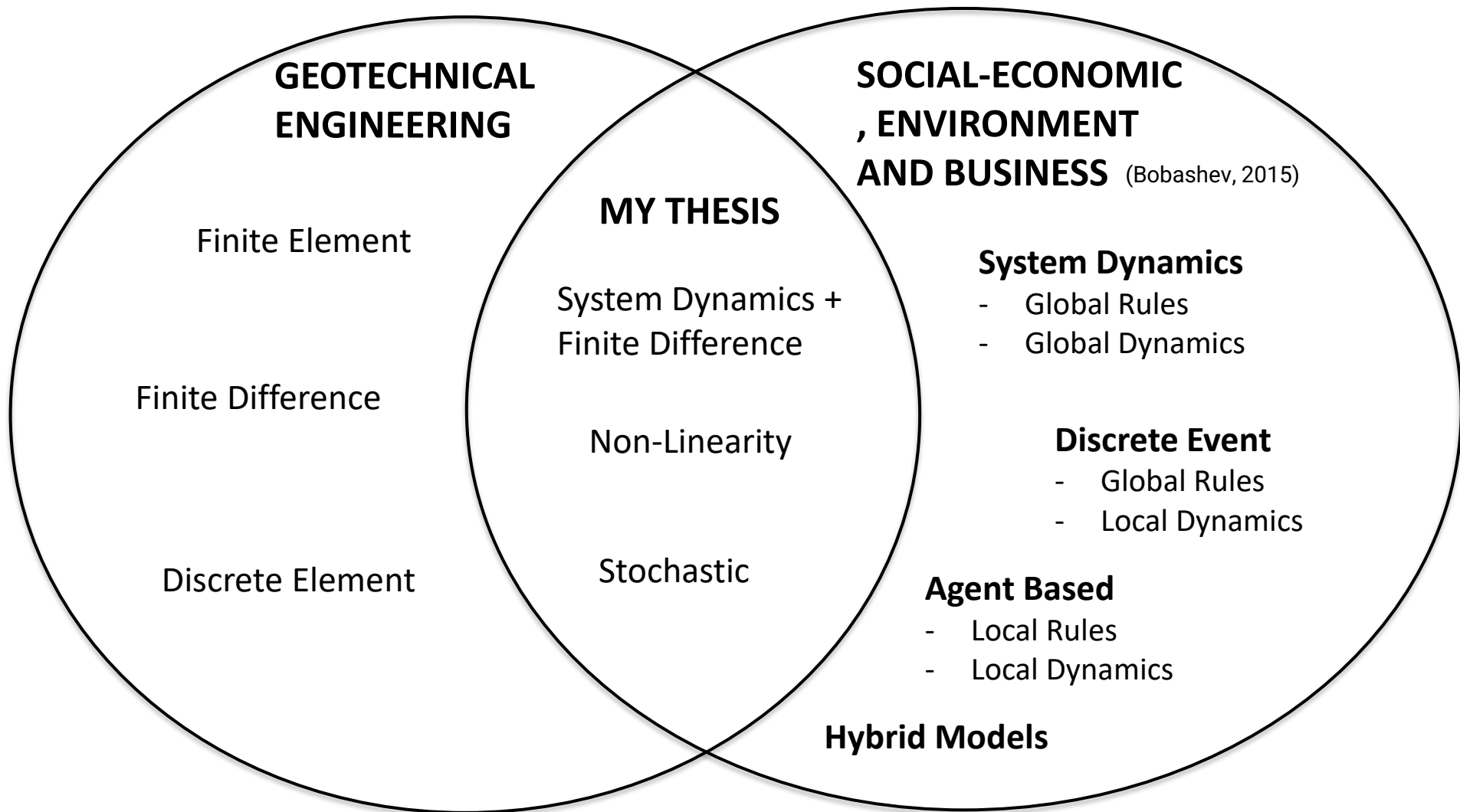
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Agenda

- **Introduction:** System Dynamics and Causal Loop Diagrams (CLD)
- **Case Study:** Soil Water Dynamics of Tailings Cap
 - Part I: Modelling Process
 - Part II: Results
- **Concluding Remarks**

The Modelling Universe



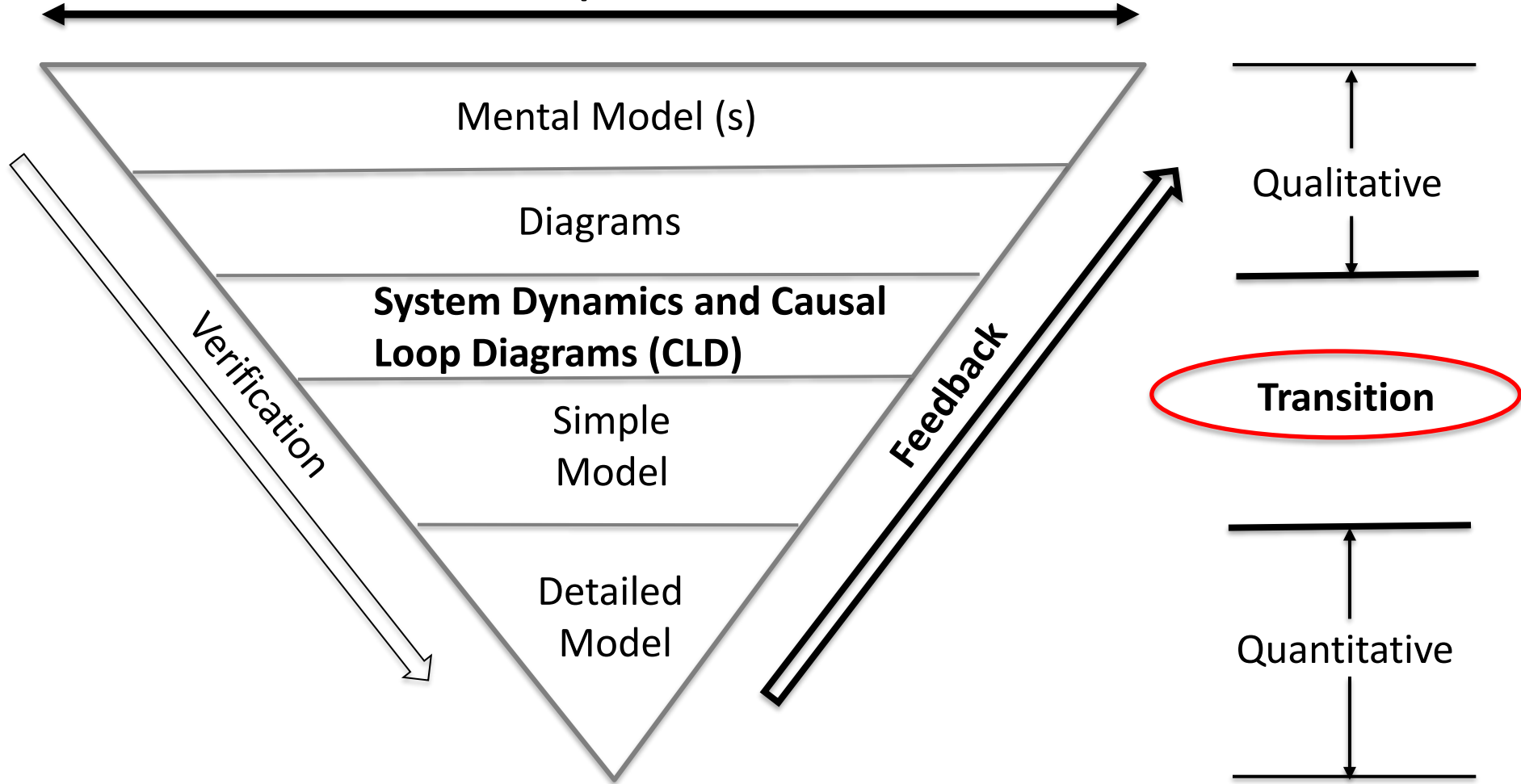
What is System Dynamics?



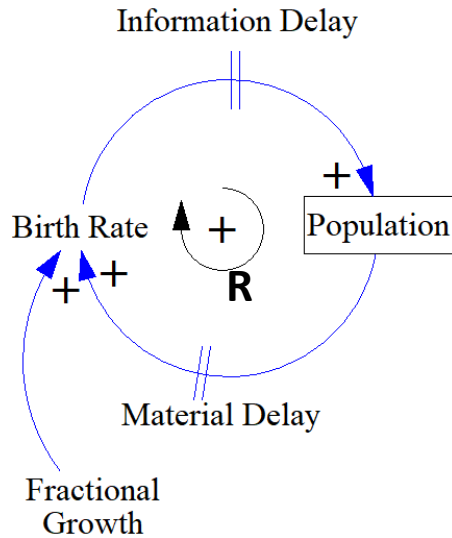
- Developed by Jay Forrester at MIT's Sloan Business School in the 50s:
To model complex inter-relationships between elements within a system or multiple systems.
- Feedbacks, Feedbacks and Feedbacks
- Applications in Public Health, Management Consulting, Water Resource Management, Public Policy, International Relations, Defense and Securities etc.

System Dynamics Modelling Process

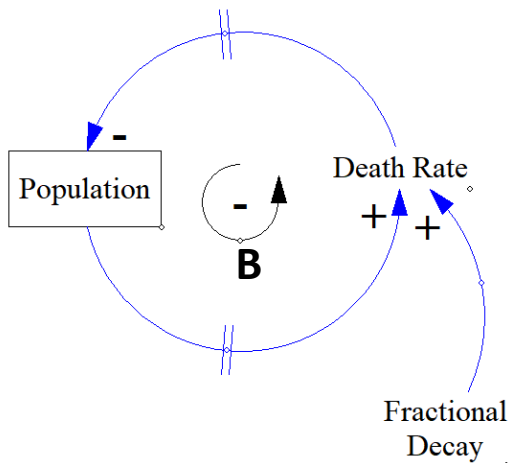
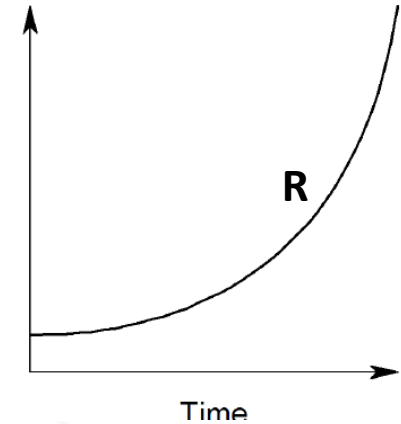
Amount of Time Spent in the Real World



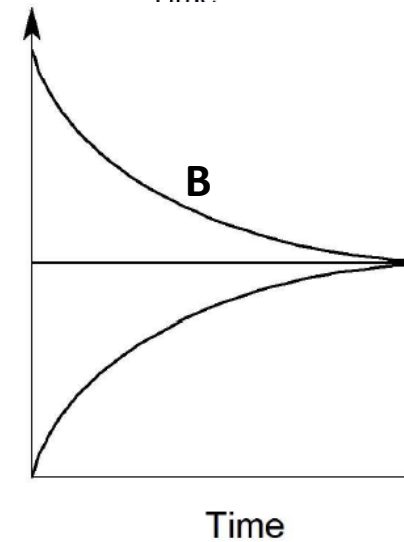
A Simple Example of Causal Loop Diagrams



R: Reinforcing

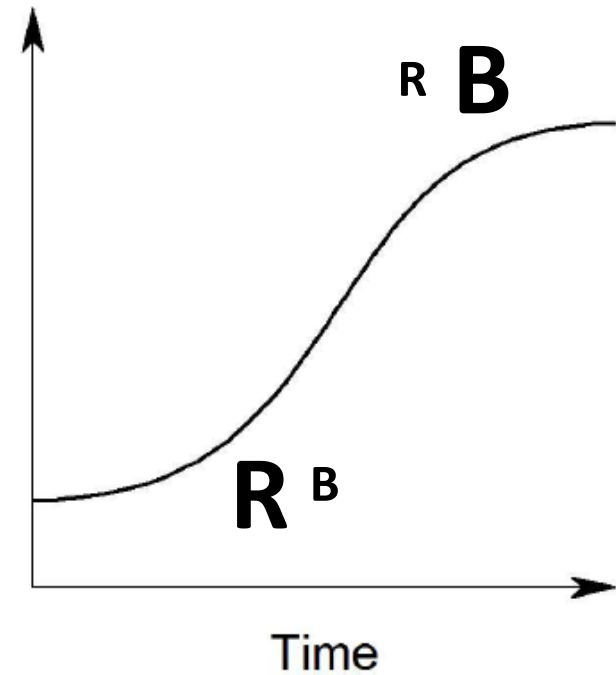
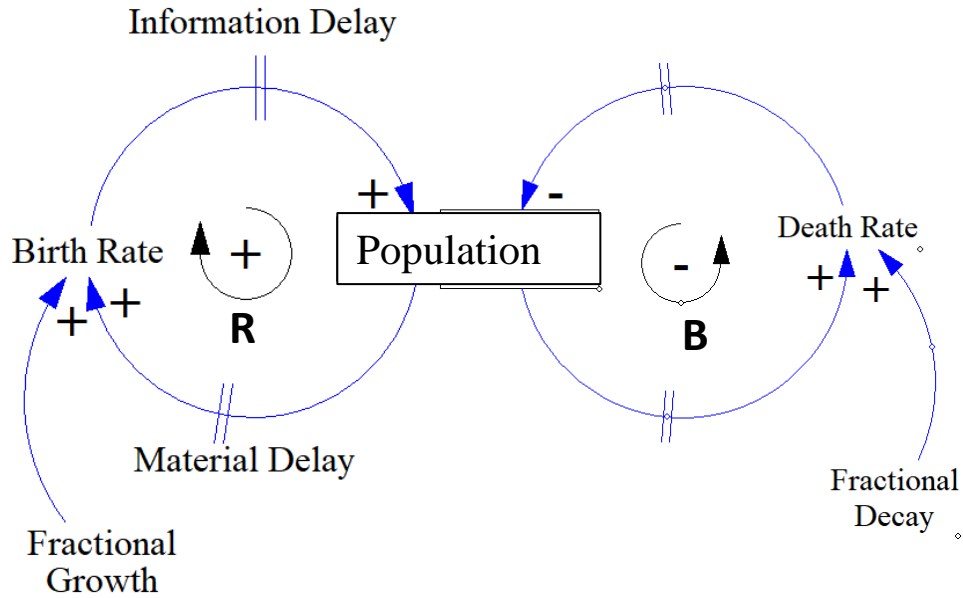


B: Balancing



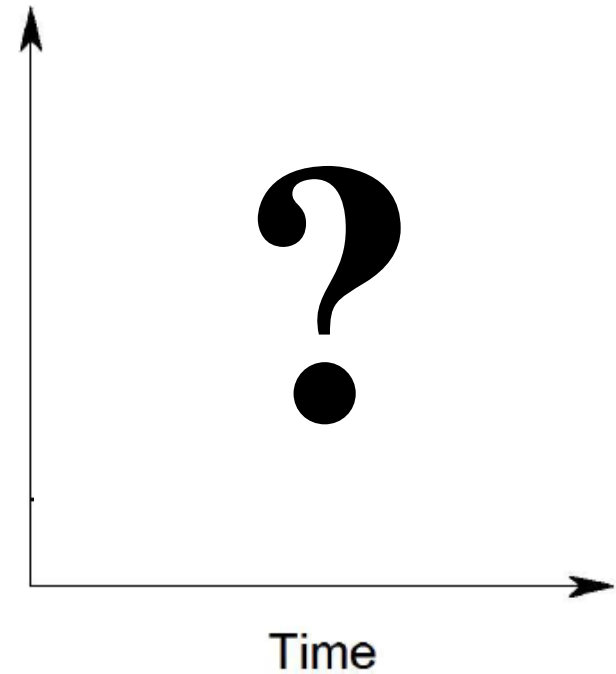
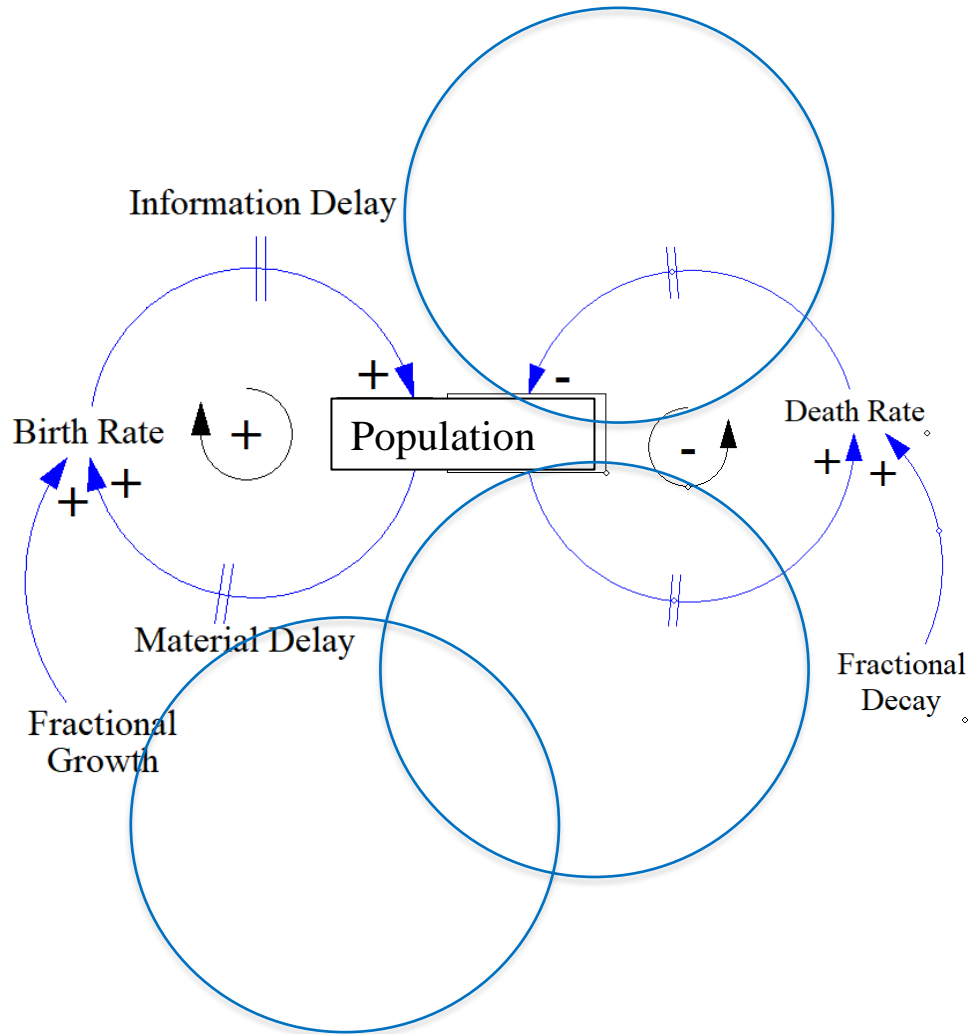
Modified from Sternman, 2000

A Simple Example of Causal Loop Diagrams



Modified from Sternman, 2000

A Simple Example of Causal Loop Diagrams



Case Study

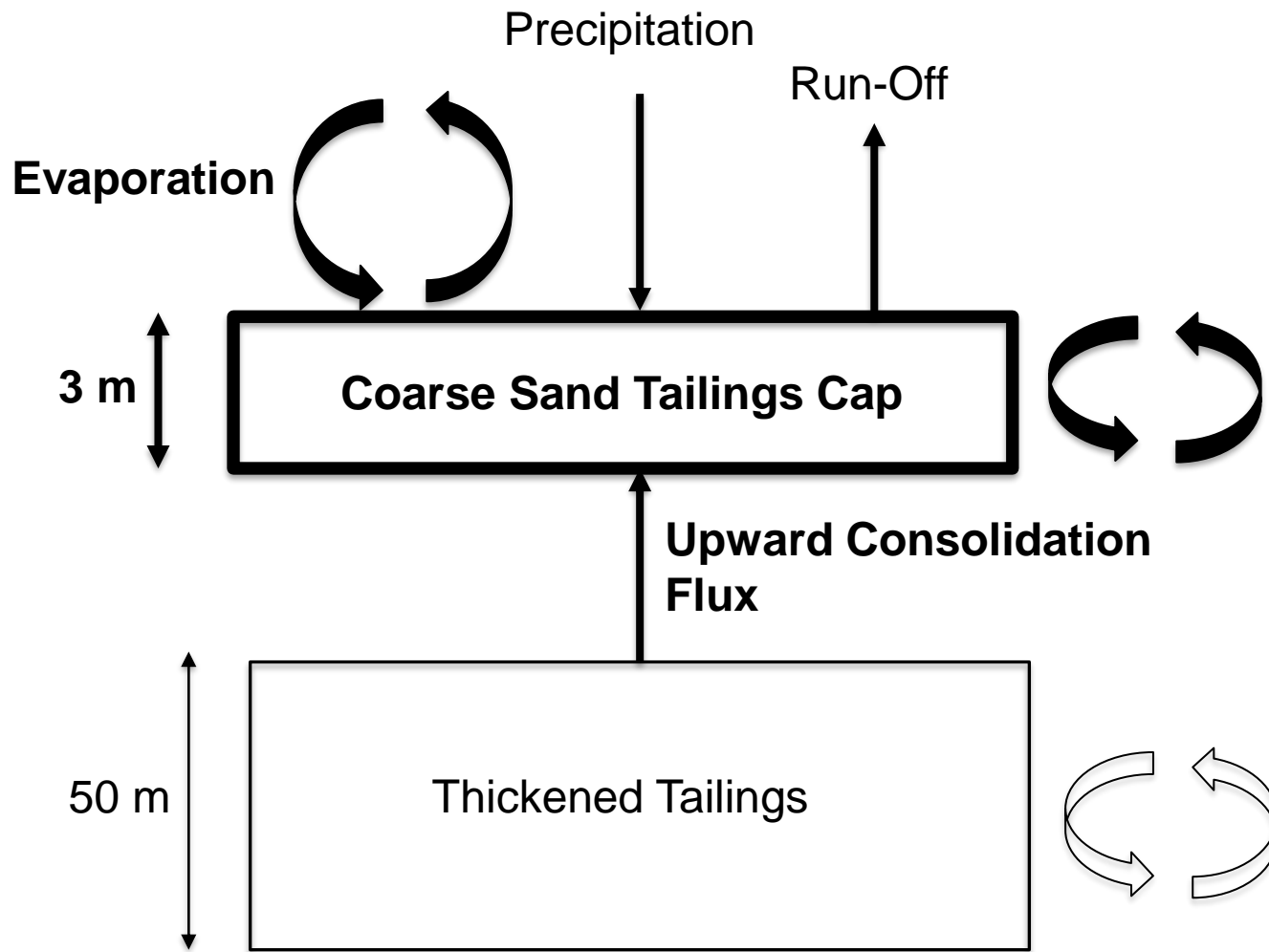


Soil Water Dynamics of Tailings Cap

Part I: Model Building Process

Part II: Simulation and Analysis

Step 0 – Conceptualization



Step 1: Pick the Governing Equations

Vol Water Content

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

Hydraulic Conductivity

$$K(\theta) = \begin{cases} K_s S_e^{1/2} [1 - (1 - S_e^{1/m})^m]^2 & S_e < 1 \\ K_s & S_e = 1 \end{cases}$$

Relative Saturation

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

Inter-Layer Transmission Rate

$$f_i = -\frac{1}{2} [K_{i-1}(\theta_{i-1}) + K_i(\theta_i)] \left(\frac{h_i - h_{i-1}}{L_{i-1} + L_i} - 1 \right)$$

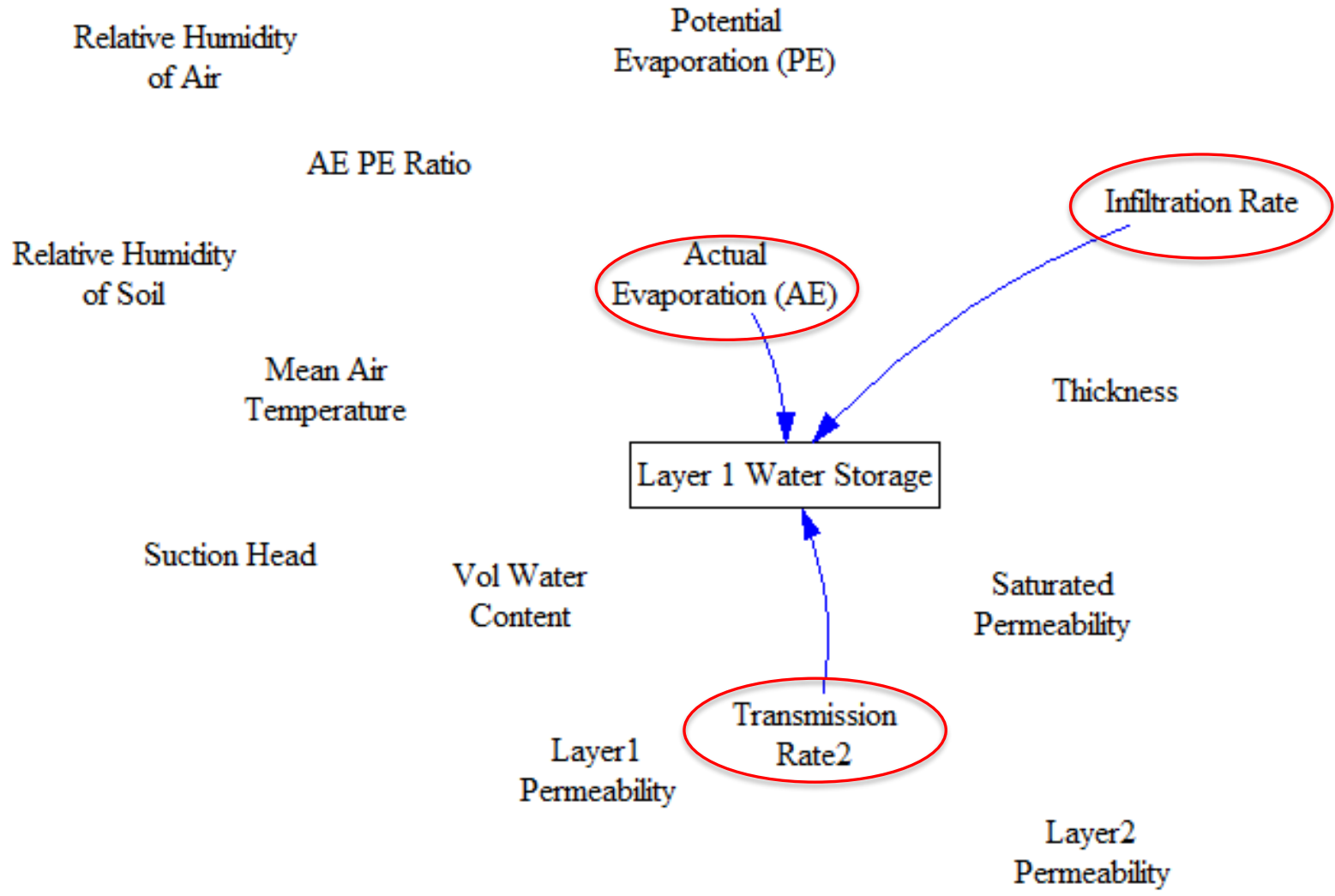
Evaporation-Suction Model

$$h_r = \exp\left(\frac{\Psi_g W_v}{RT}\right)$$

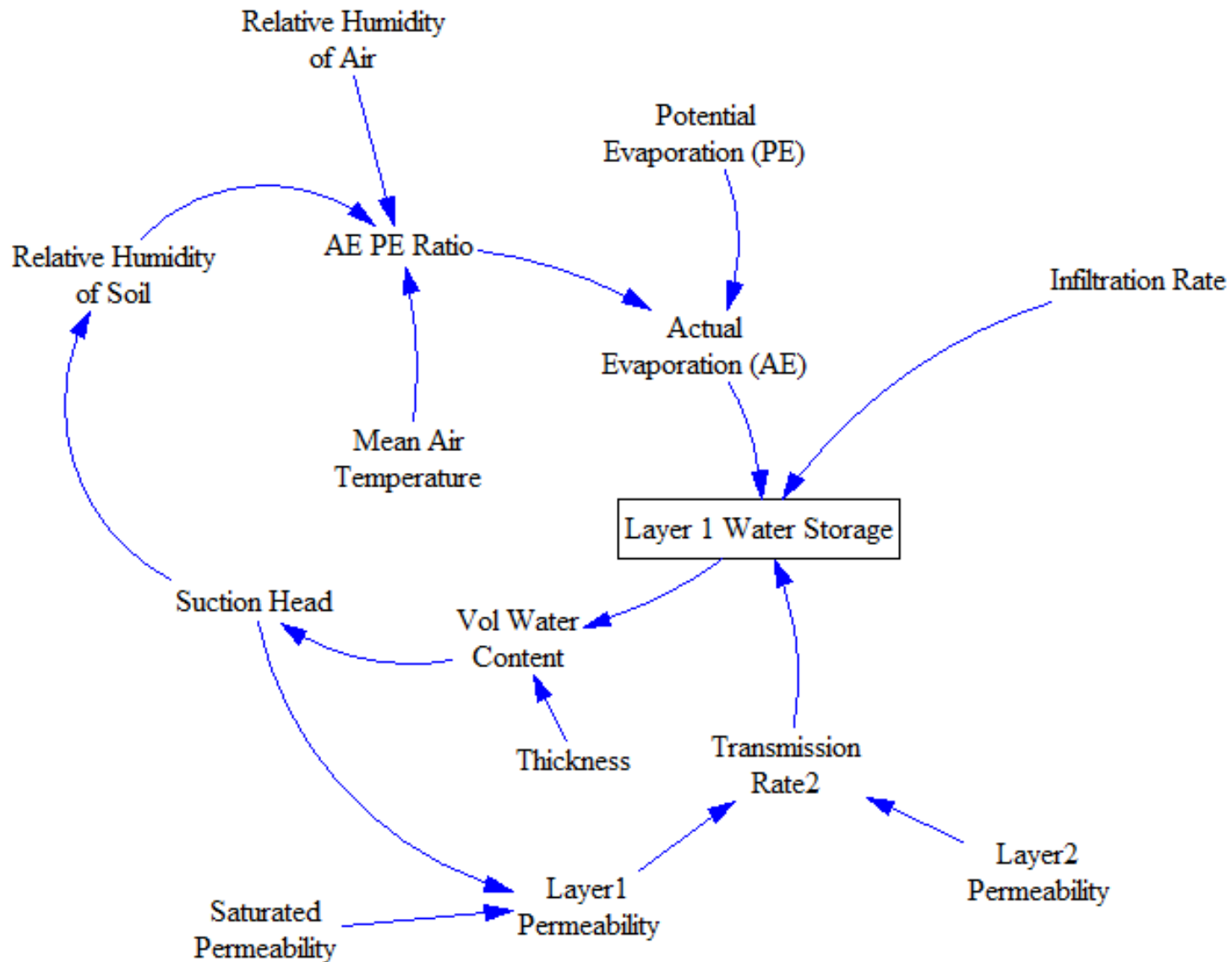
Actual Evaporation Rate

$$\frac{AE}{PE} = \left[\frac{\exp\left(\frac{\Psi_g W_v}{RT}\right) - h_a}{1 - h_a} \right]$$

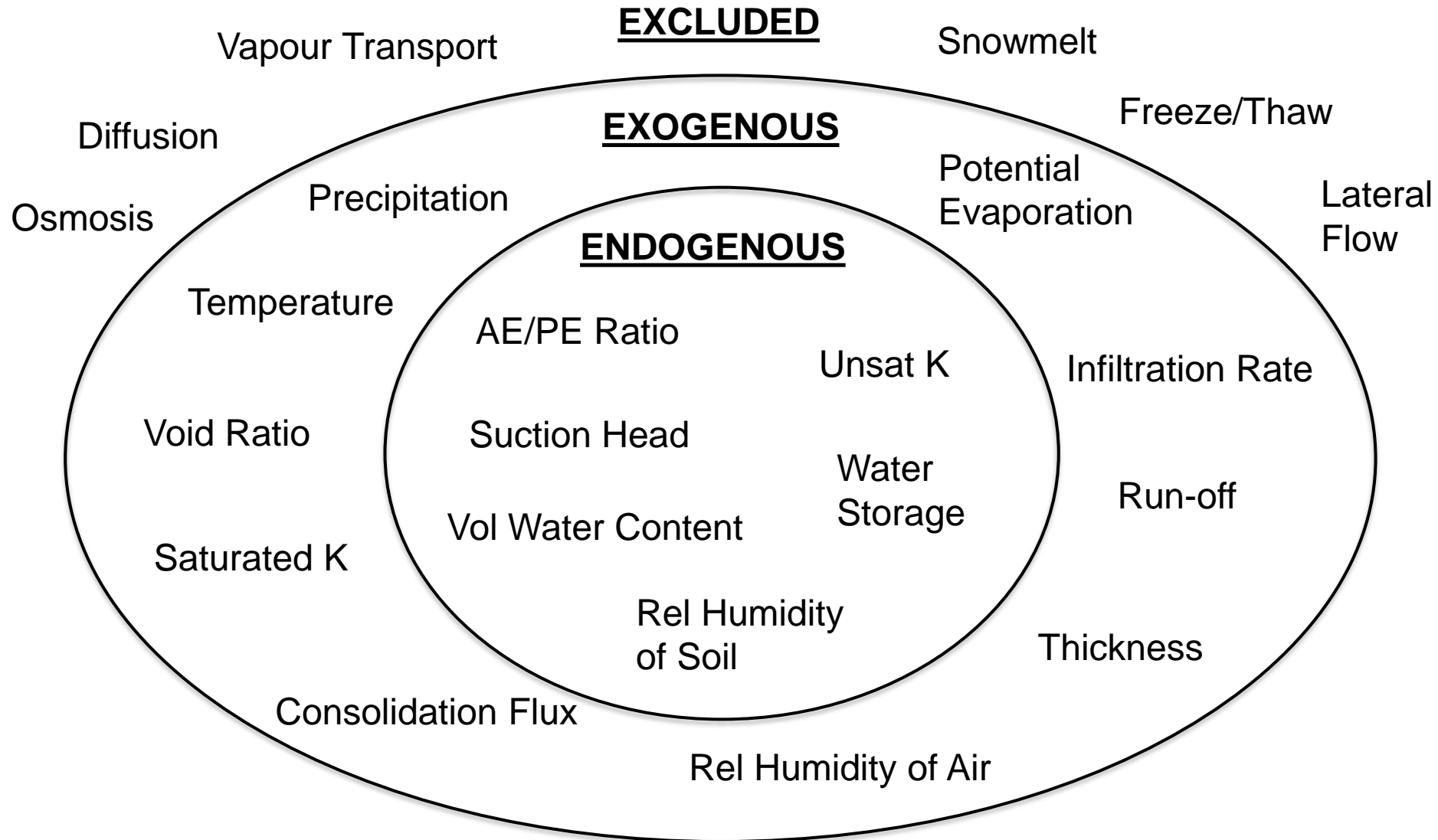
Step 2: List relevant variables; identify the stock(s) and flows



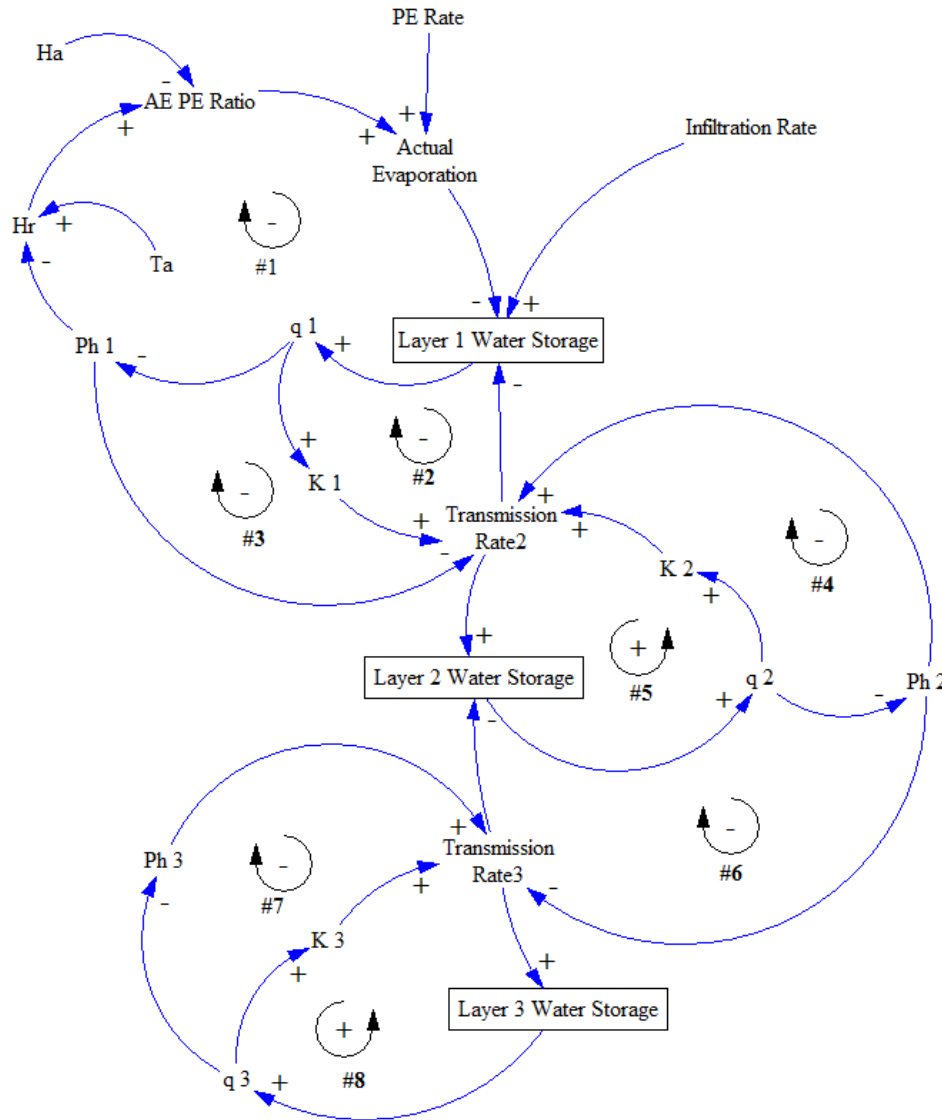
Step 3: Construct the preliminary CLD; Identify feedbacks; discuss and debate



Step 4: Use the Bull's Eye Diagram to identify the boundary of the model / system



Step 5: Build the partial CLD; add polarity signs and identify feedback structures



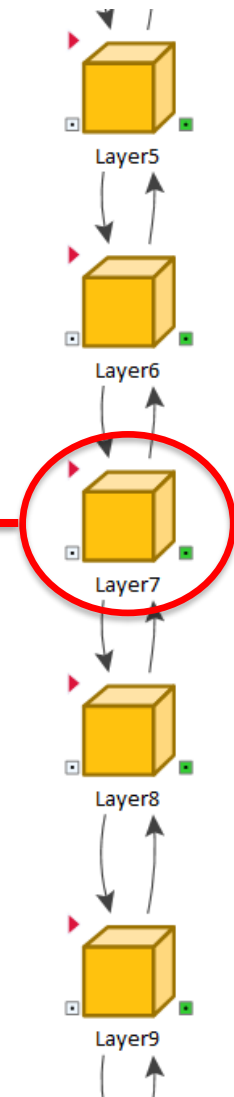
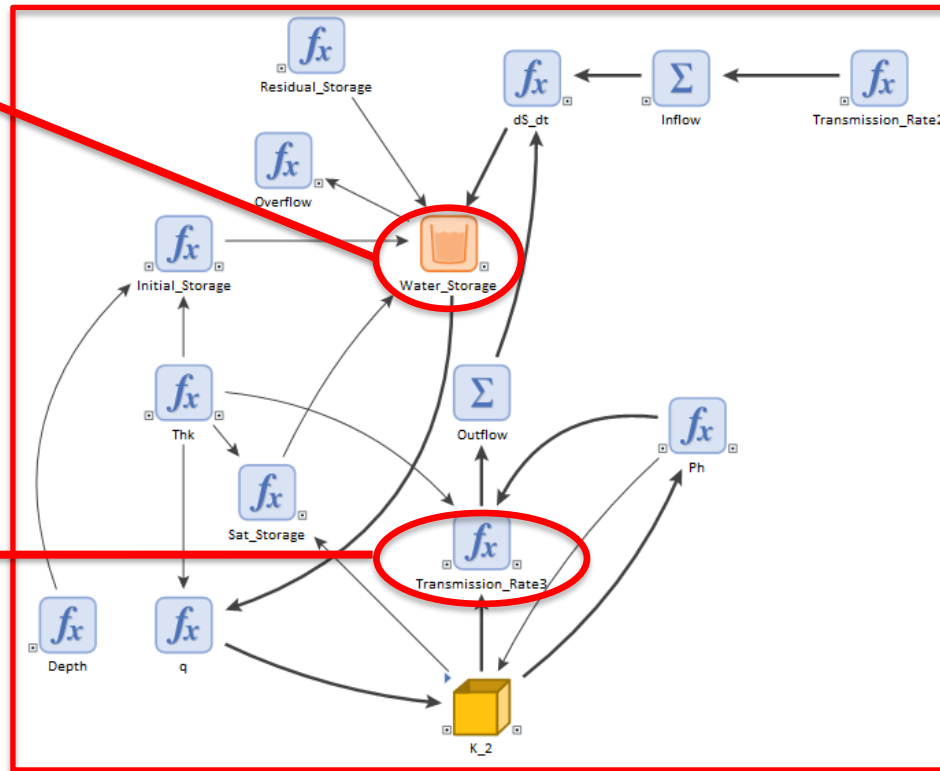
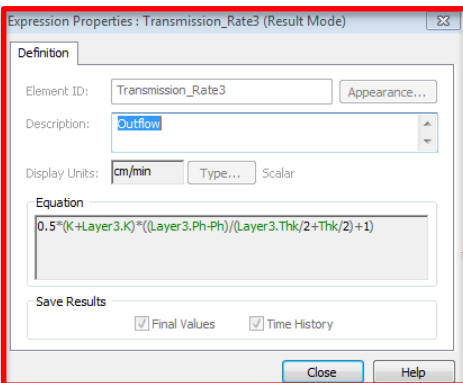
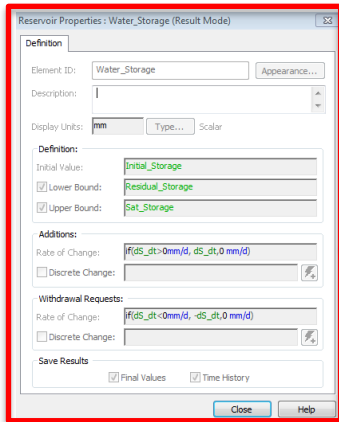
Negative (Balancing) Loop

- Suction-Driven
- Dominates when evaporation > precipitation

Positive (Reinforcing) Loop

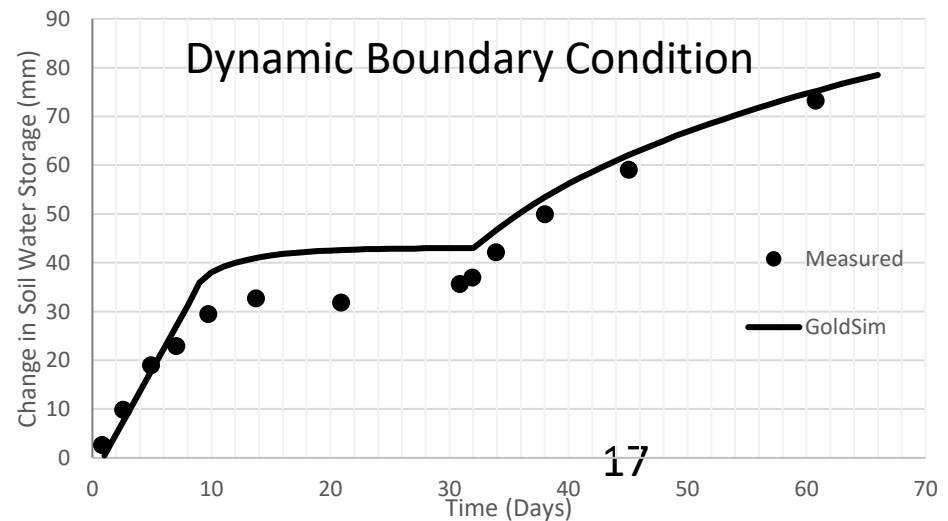
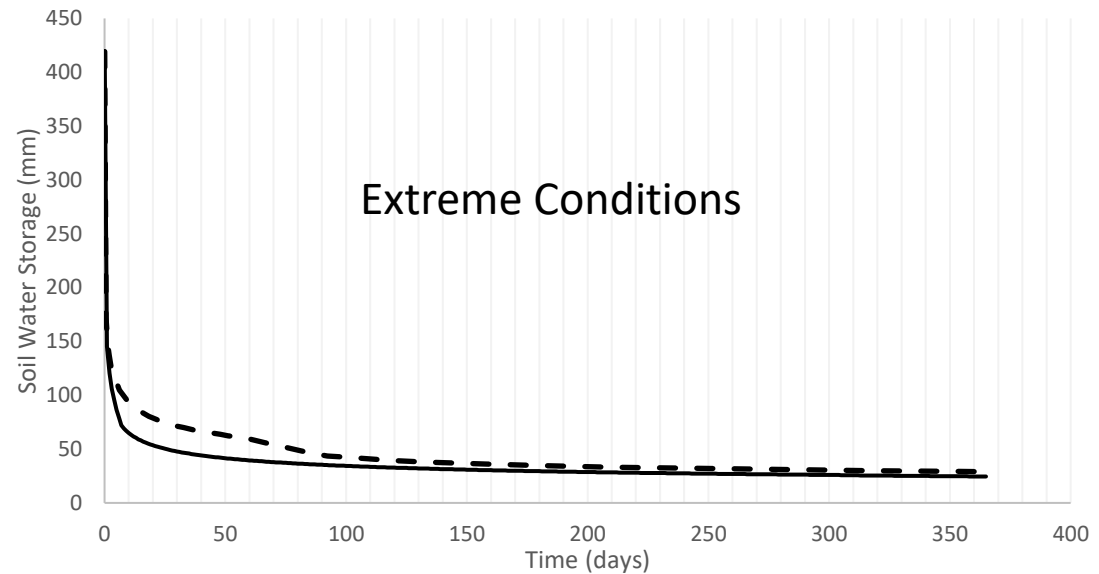
- Infiltration-Saturation Driven
- Dominates when precipitation > evaporation or when wetting front arrives

Step 6: Transform CLDs into GoldSim



Step 7: Validation

Step 7: Run and validate simple models under a variety of conditions and different materials.



Step 8: Visualization and User Interface

Step 1: Geometry and Soil Properties

	(cm)	(cm)	(cm-1)		(cm/min)		
	Depth	Thickness	Gr	Gs	alpha	n	Ks
1	8.33335	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
2	25.00003333	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
3	41.6667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
4	58.33336667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
5	75.00003333	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
6	91.6667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
7	108.3333667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
8	125.0000333	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
9	141.6667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
10	158.3333667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
11	175.0000333	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
12	191.6667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
13	208.3333667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
14	225.0000333	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
15	241.6667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
16	258.3333667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
17	275.0000333	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072
18	291.6667	16.6666667	0.012	0.428	0.02259243	5.4848	0.0072

Step 3: Simulation Settings

Time Setting: Calibration:

Go to Output

Calibration Mode:

Model Structure



Step 2: Boundary Conditions

Constant Infiltration: cm/min

Constant Evaporation: cm/min

Bottom Downward Flux: cm/min

Bottom Upward Flux: cm/min

Residual_Suction (kPa): Initial Water Content:

Profile_Time (day): Submodel_Duration (d):

Upper Boundary Inflow Condition:

Upper Boundary Outflow Condition:

Lower Boundary Outflow Condition:

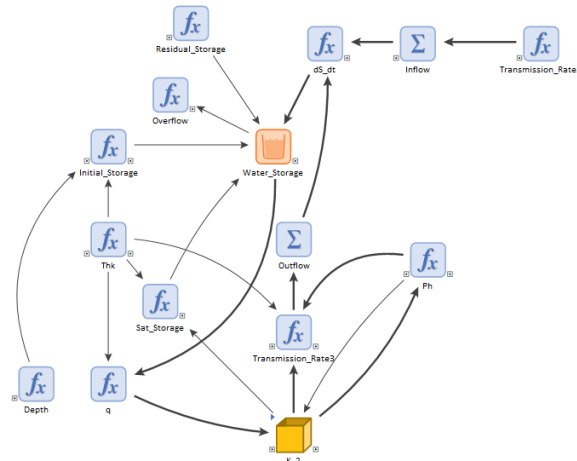
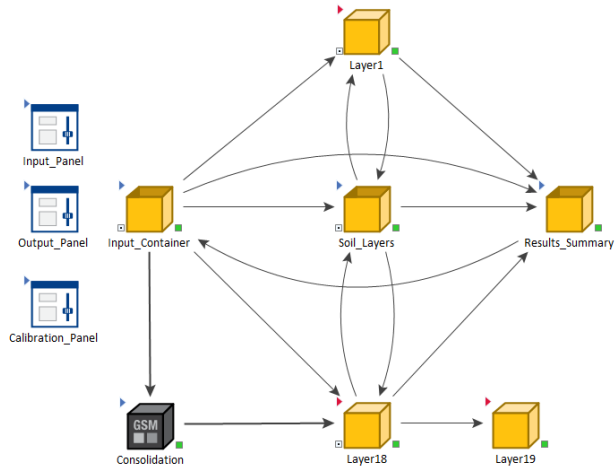
Lower Boundary Inflow Condition: Consolidation Input:

Climate Data:

User Input

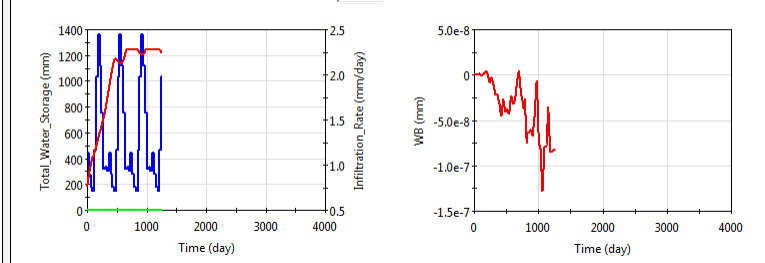
User sees what the modeler sees

Model Overview



Layer Setup

Simulation Results



Real-Time Simulation Results

Return to Input

Go to Calibration

Run

Final Steps



Step 9:

Go back to the Bull's Eye Diagram if required as part of the iterative and participatory modelling process

Step 10:

Parameter Estimation (Case Study)

Step 11:

Simulation and Sensitivity Analysis (Case Study)

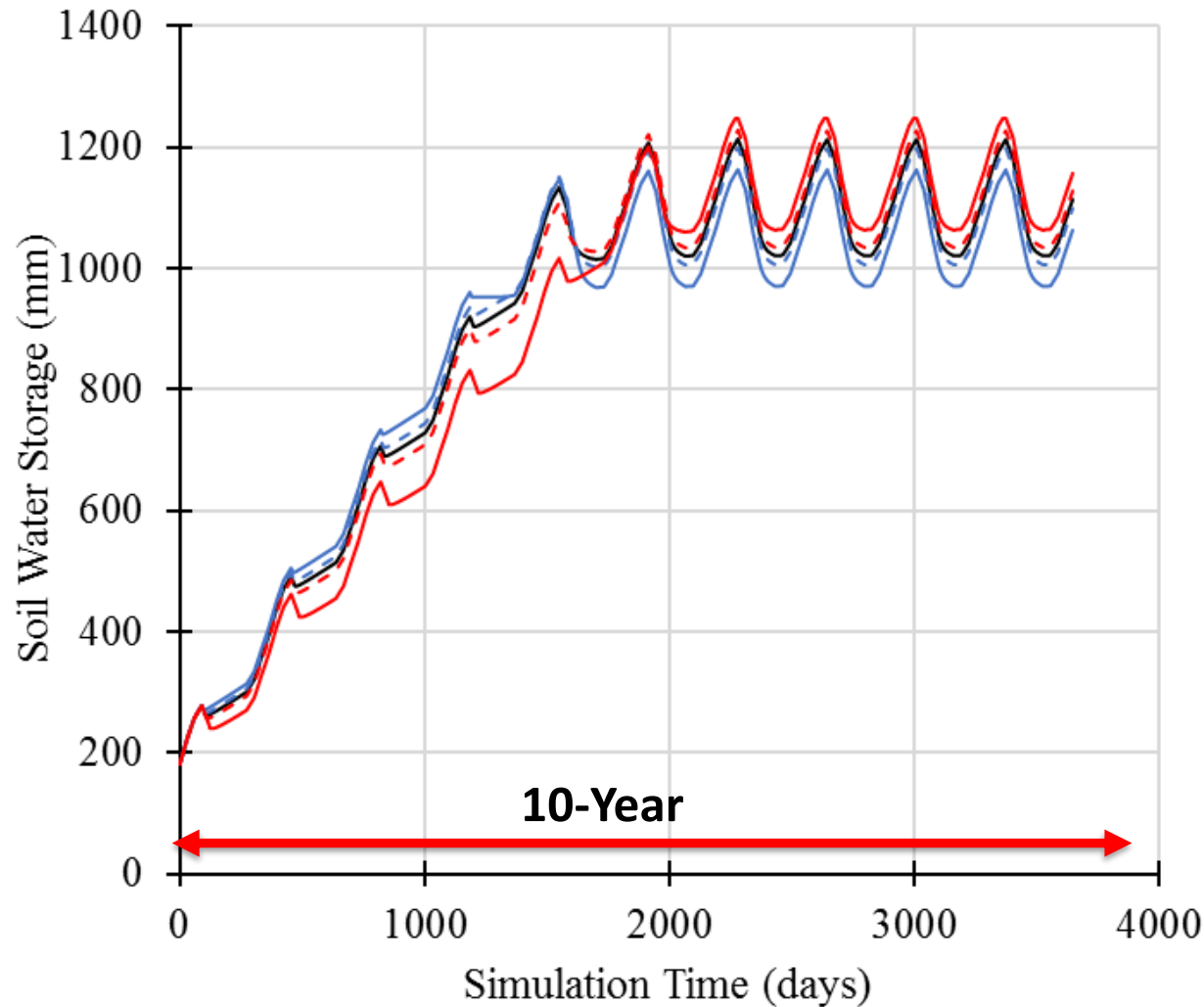


Soil Water Dynamics of Tailings Cap

Part I: Model Building Process

Part II: Simulation and Analysis

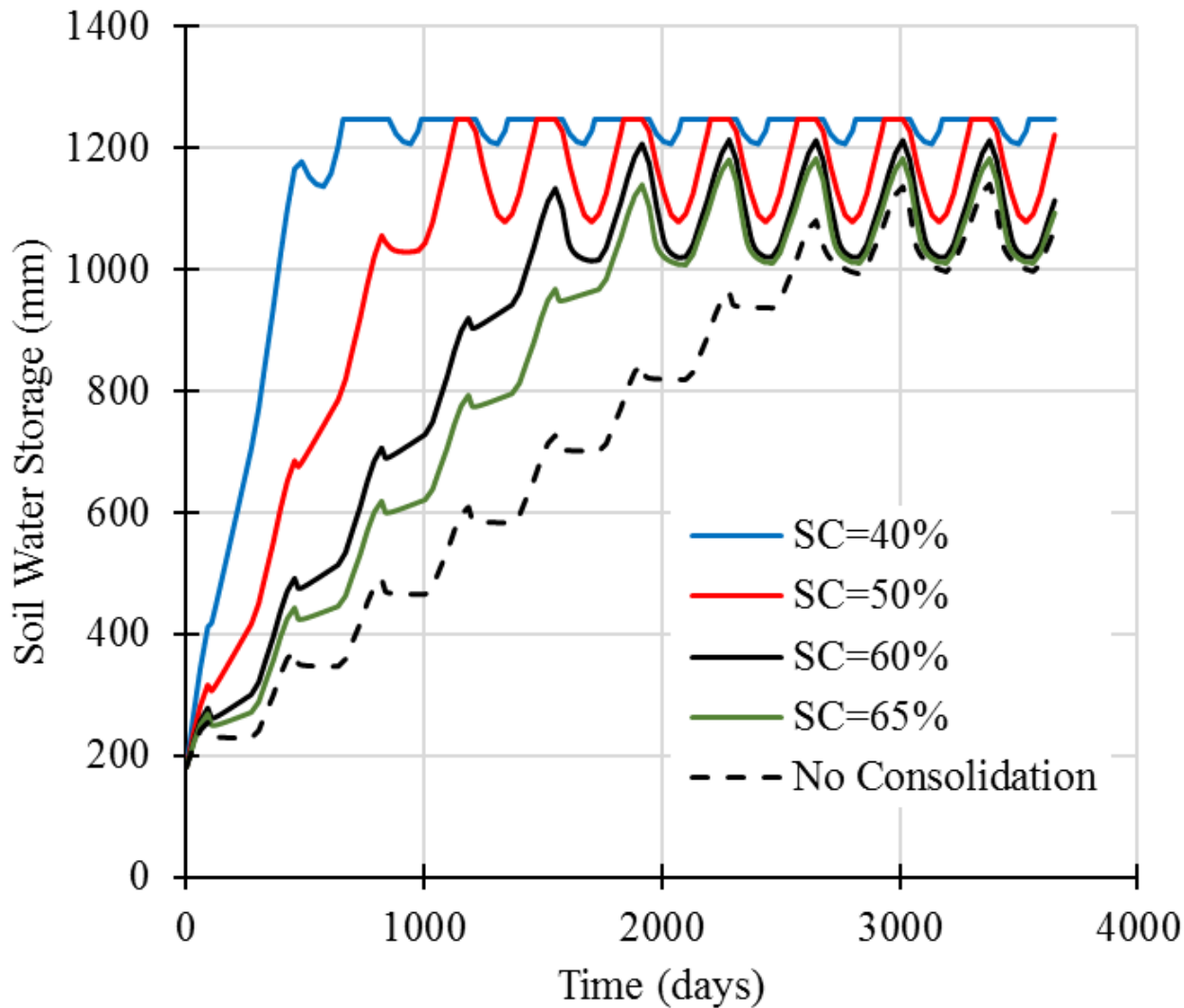
Global Dynamics– Total Water Storage



Vary Saturated Hydraulic Conductivity of CST

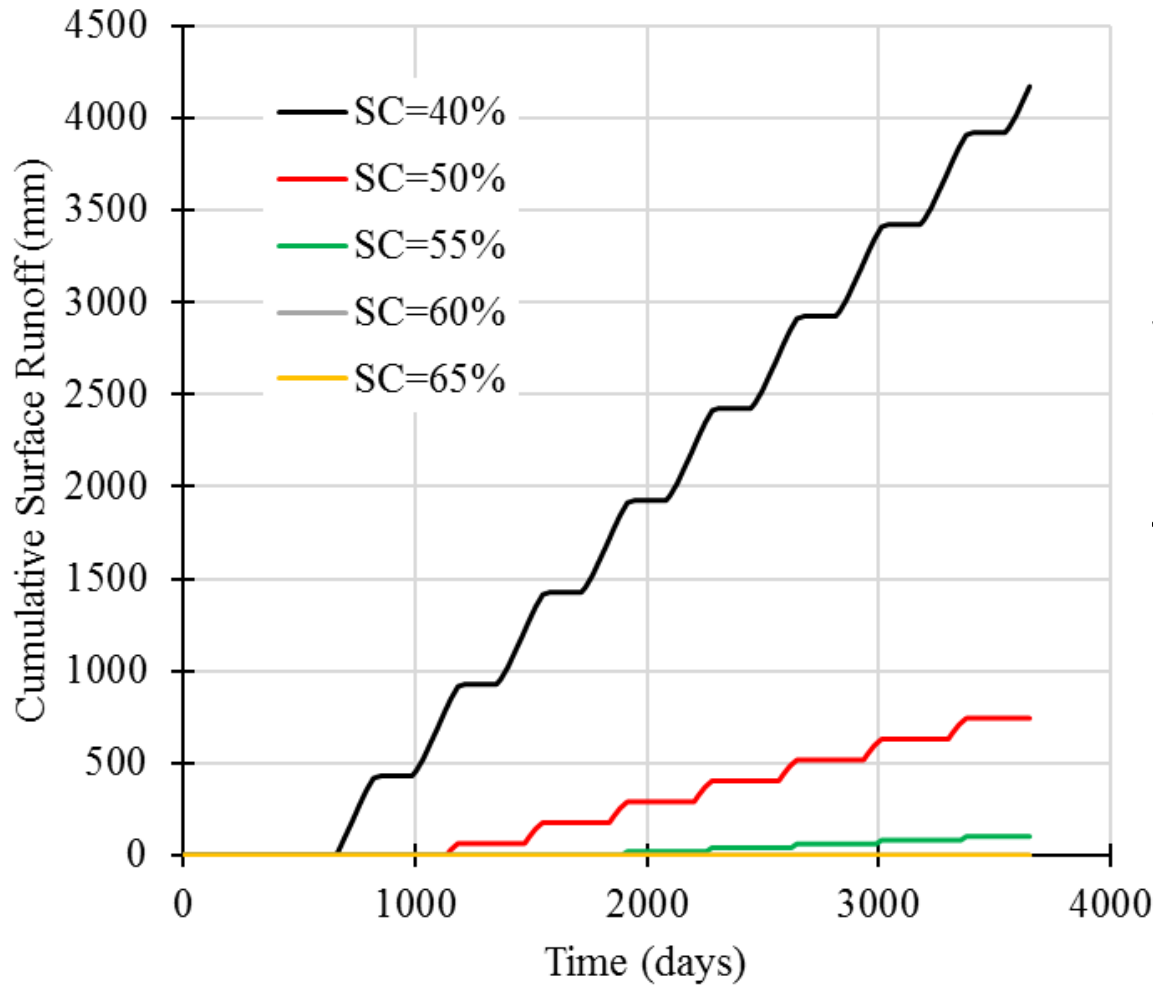
Initial SC of TT = 60%

Global Dynamics– Total Water Storage



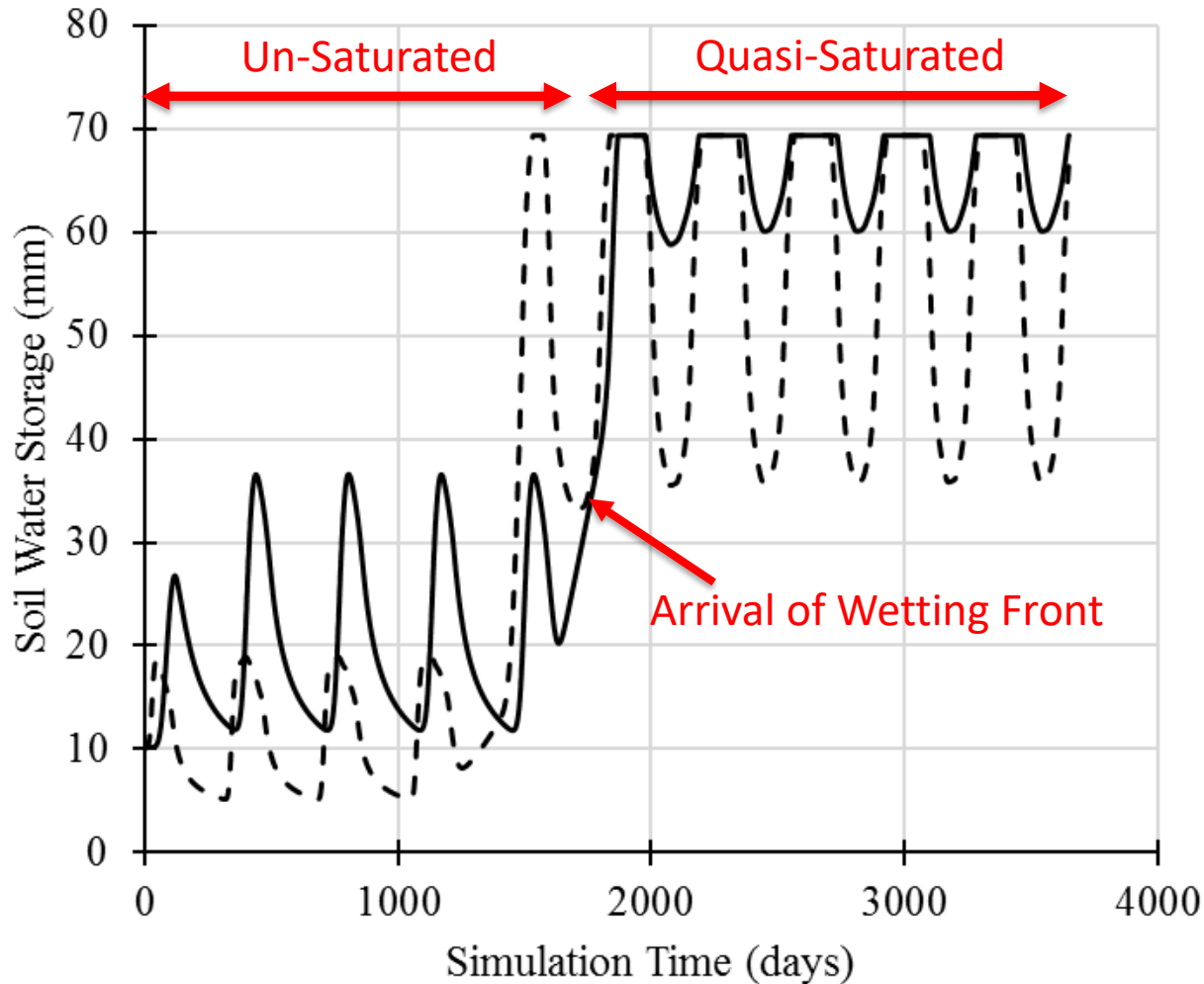
Vary Initial SC of TT
Same CST Ks in all scenarios

Global Dynamics– Cumulative Runoff



What is the minimum initial SC of TT required to prevent consolidation release water from daylighting at the surface?

Local Dynamics - Layer 4 (Depth: 52 cm)



Dashed Line: Higher Ks
Solid Line: Lower Ks

Concluding Remarks

- **Why System Dynamics?**
 - Feedback Structures
 - Rigorous Qualitative Process
 - Foster thinking and shared understanding through participatory modelling exercises
 - Ability to model soft variables

Concluding Remarks



- **Limitations**
 - Poor Capture of Spatial Variation
 - Over-Simplification
 - Over-Complexity
 - Complacency?

Acknowledgements

- Dr Nicholas Beier



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FSCA (Dr Silawat Jeeravipoolvarn)