NSERC/COSIA Industrial Research Chair in
Oil Sands Tailings Geotechnique

Development of an integrated tailings closure model using GoldSim: preliminary results and lessons learned

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cosia CANADA'S OIL SANDS INNOVATION ALLIANCE

Alberta Innovates Energy and Environment Solutions

NSERC CRSNG

Agenda

- **Introduction**: System Dynamics and Causal Loop Diagrams (CLD)

- **Case Study**: Soil Water Dynamics of Tailings Cap

  Part I: Consolidation

  Part II: Unsaturated Flow

- **Concluding Remarks**

What is System Dynamics ?

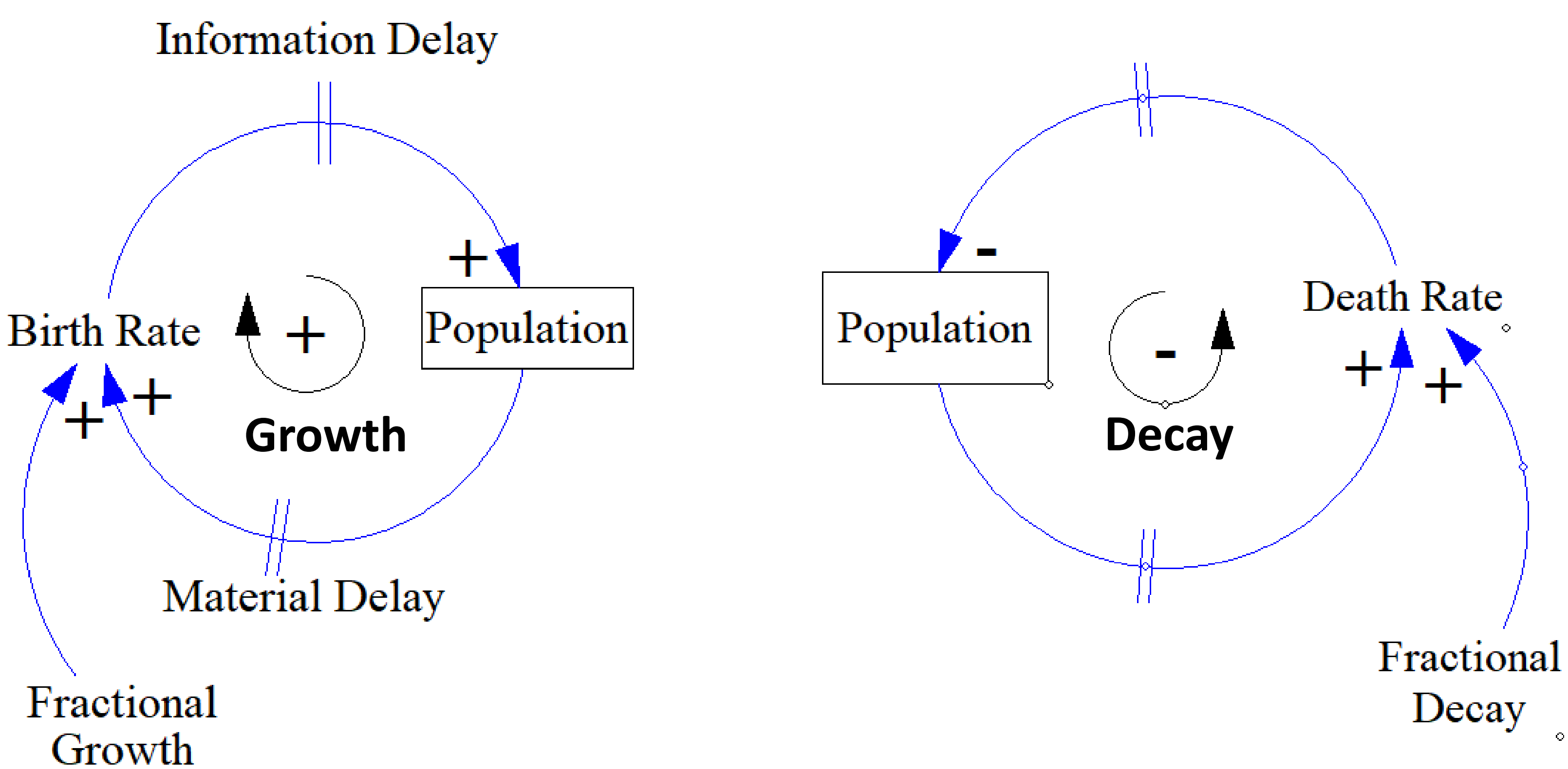
– Developed by Jay Forrester at MIT’s Sloan Business School in the 50s:

To model complex inter-relationships between elements within a system or multiple systems.

- Feedbacks, Feedbacks and Feedbacks

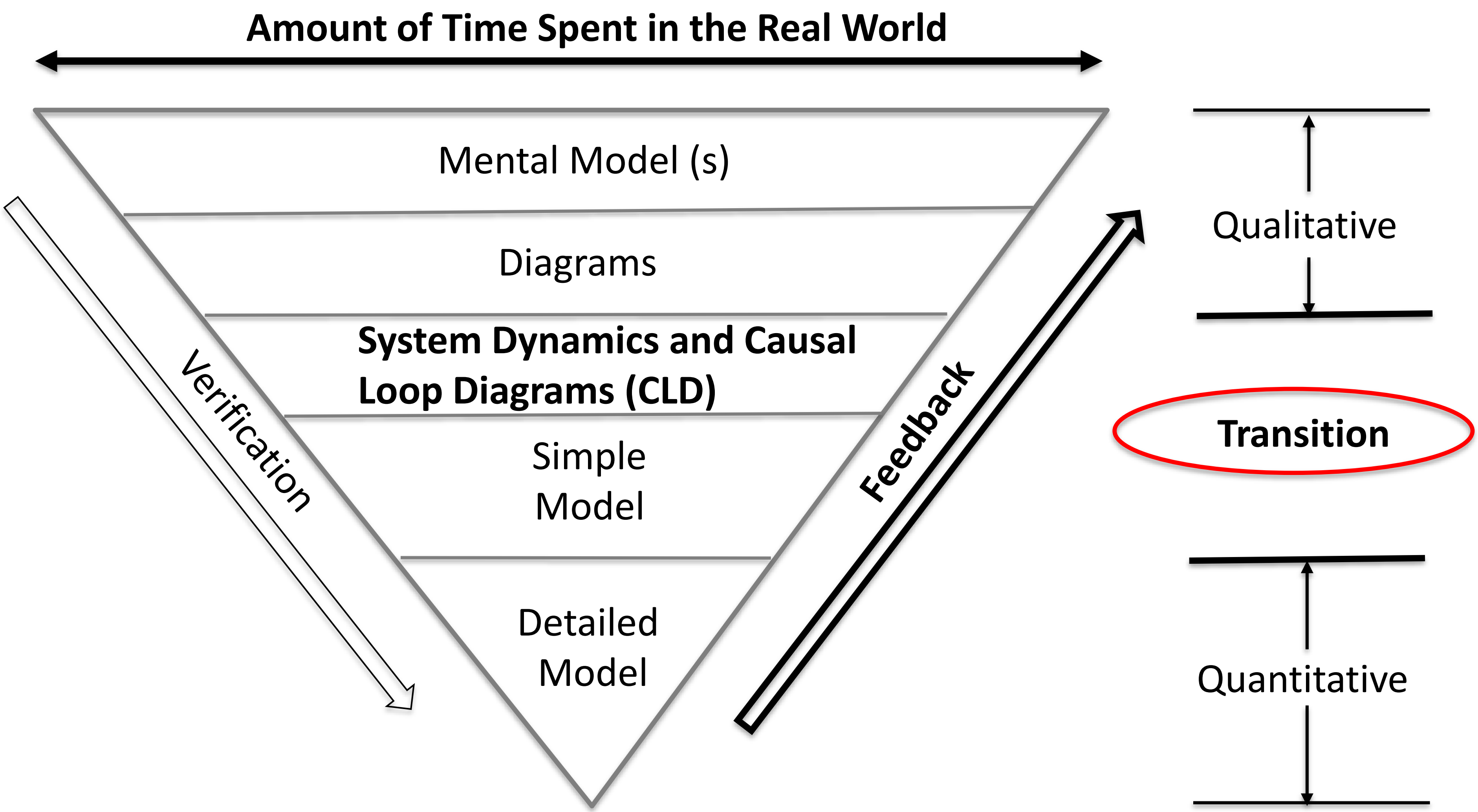
– Applications in Public Health, Management Consulting, Public Policy, International Relations, Defense and Securities etc. Increasingly used in inter-disciplinary modelling (i.e. combined management and technical models).

A Simple Example of Causal Loop Diagrams



Modified from Sternman, 2000

System Dynamics Modelling Process



Case Study

Soil Water Dynamics of Tailings Cap

Question 1: When will the tailings cap reach a steady-state in terms of water storage ?

Question 2: What are the major factors that will influence the time to reach steady-state ?

Soil Water Dynamics of Tailings Cap

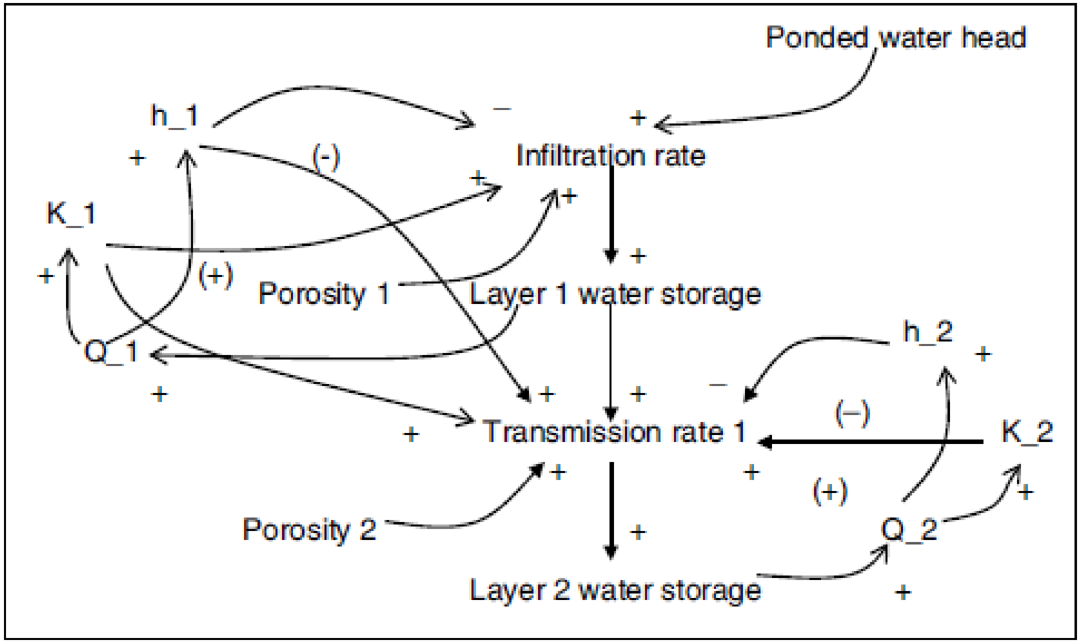
Part I: A Bottom-Up Re-Interpretation of Tailings Consolidation Flux using System Dynamics and Causal Loop Diagrams

Part II: Unsaturated Flow Interaction in Tailings Cap

Case Study

System dynamics modeling of infiltration and drainage in layered coarse soil

Mingbin Huang[1,3], Amin Elshorbagy[1,4], S. Lee Barbour[1], Julie D. Zettl[1], and Bing Cheng Si[2]



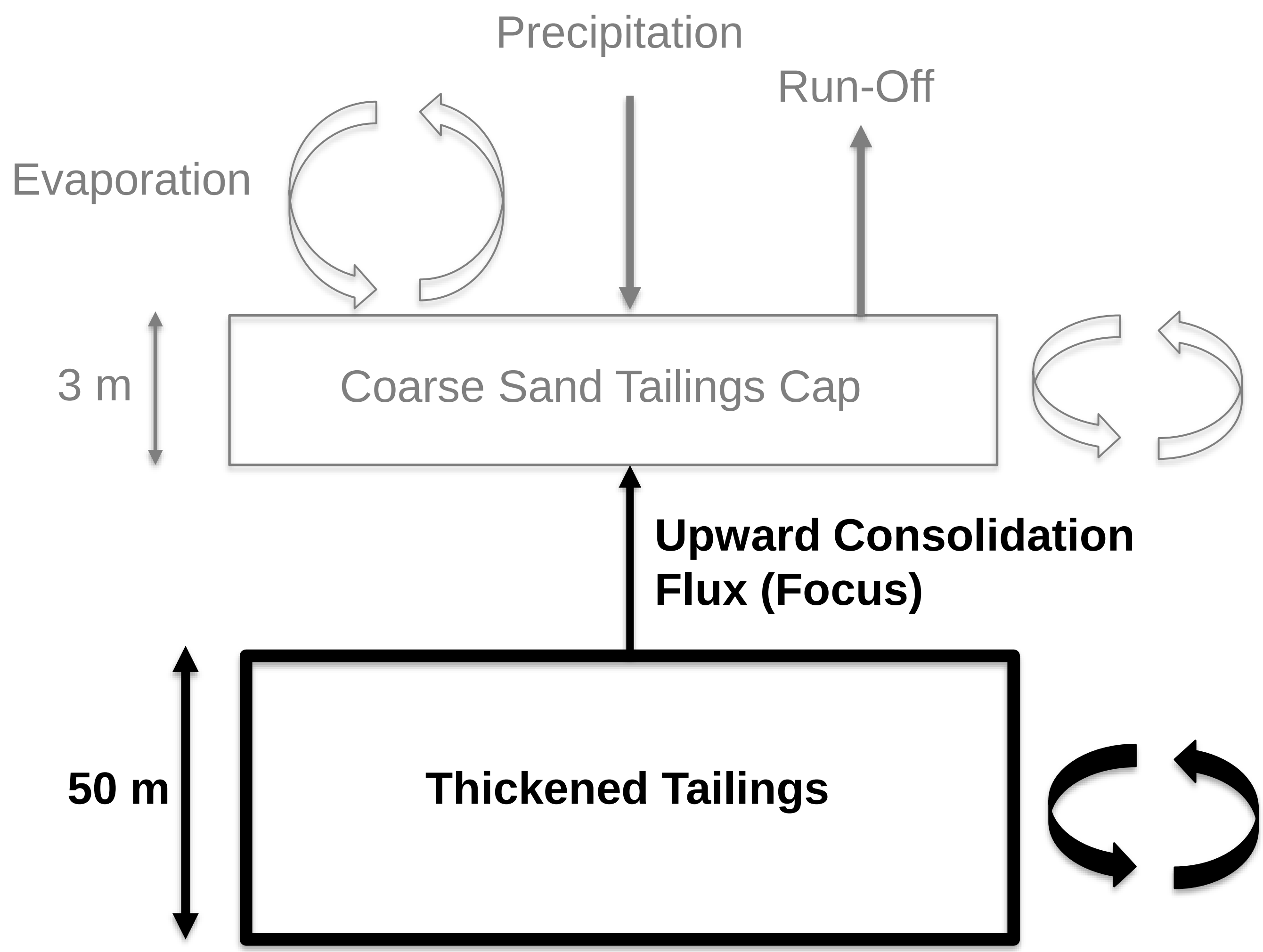
Assumptions

- Darcian Flow
- Advection-Dominated
- One-Dimensional
- No Volume Change

Key Deficiencies

- No Climatic Input
- Limited Validation
- **No Consolidation**
- Exogenous variables not shown in CLD

Case Study – Simulation Setup



Case Study – Consolidation SubModel

Solution to Differential Equations (Cargill, 1982)

$$e_{i,j+1} = e_{i,j} - \frac{\tau}{\gamma_w}\left(\left\{\gamma_c \beta(e_{i,j}) + \left[\frac{\alpha(e_{i+1,j}) - \alpha(e_{i-1,j})}{2\delta}\right]\right\}\left[\frac{e_{i+1,j} - e_{i-1,j}}{2\delta}\right] + \alpha(e_{i,j})\left[\frac{e_{i+1,j} - 2e_{i,j} + e_{i-1,j}}{\delta^2}\right]\right)$$

De-compose

De-compose

Temporal Components

B_e a_e Void_Ratio

dStress_de

Hydraulic_Conductivity

Spatial Components

de_dz d2e_dz2

Neighbour_Void_Ratio

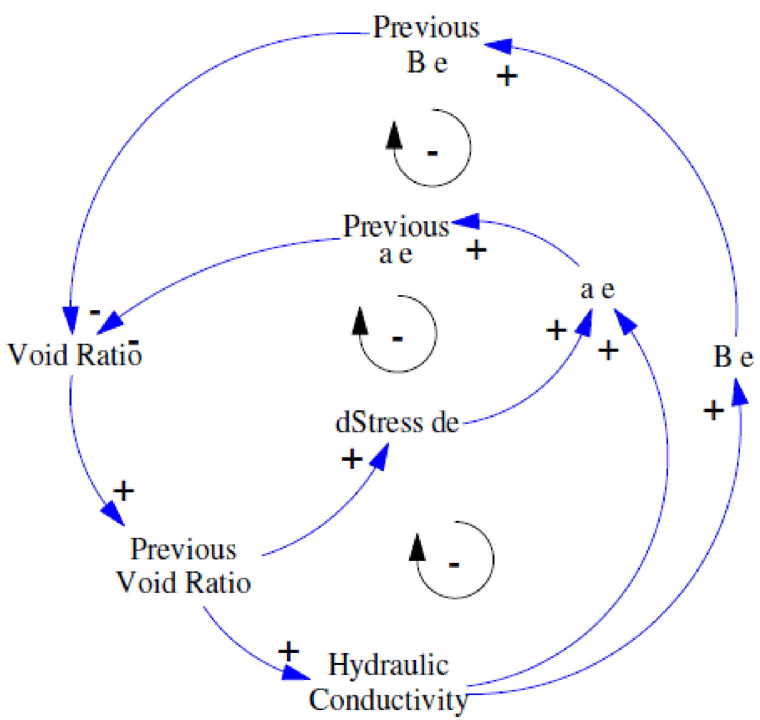
Neighbour_a_e delta_z

Neighbour_dStress_de

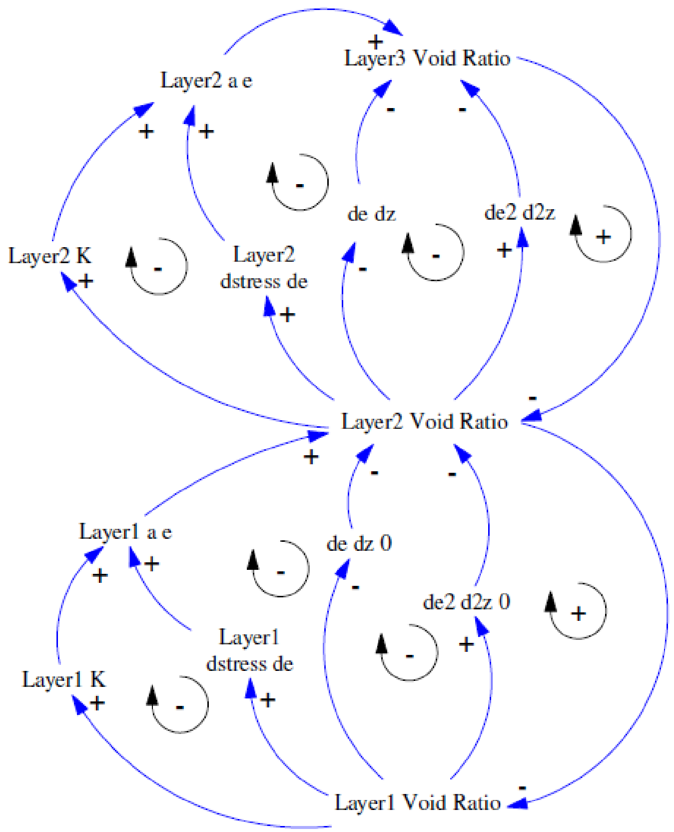
Case Study – Consolidation SubModel

What kind of narrative and conclusion can we make by just looking at those CLDs?

Temporal Feedback

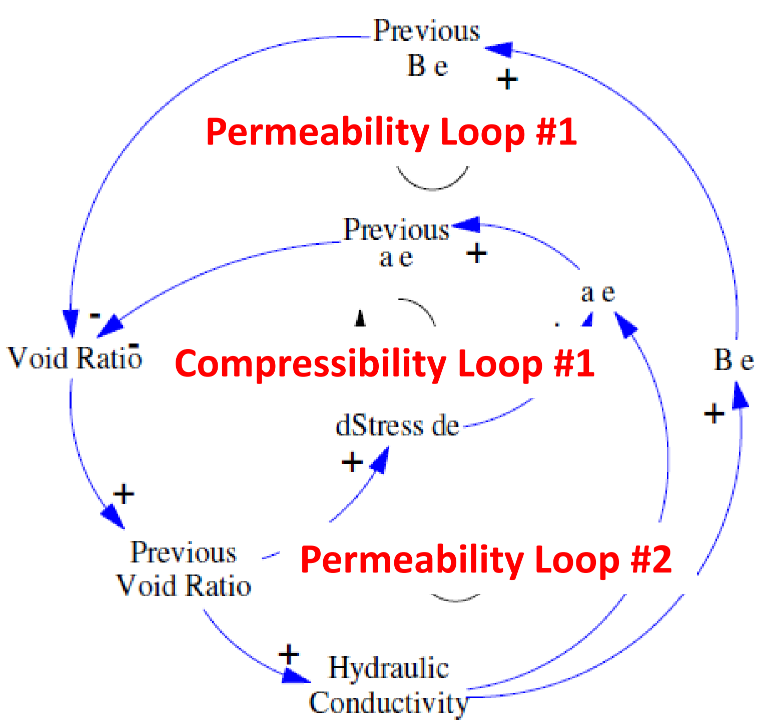


Spatial Feedback

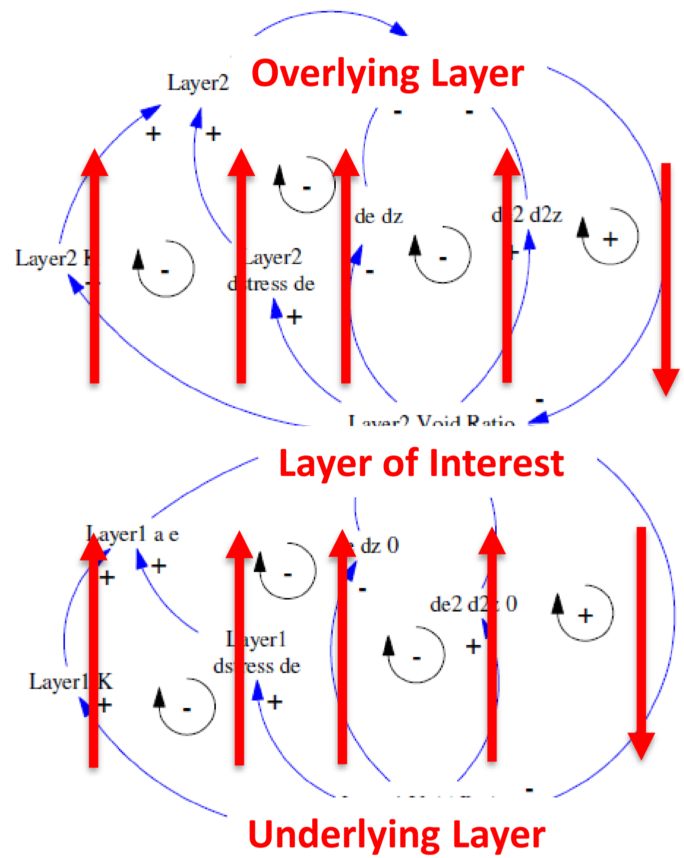


Case Study – Consolidation SubModel

Temporal Feedback



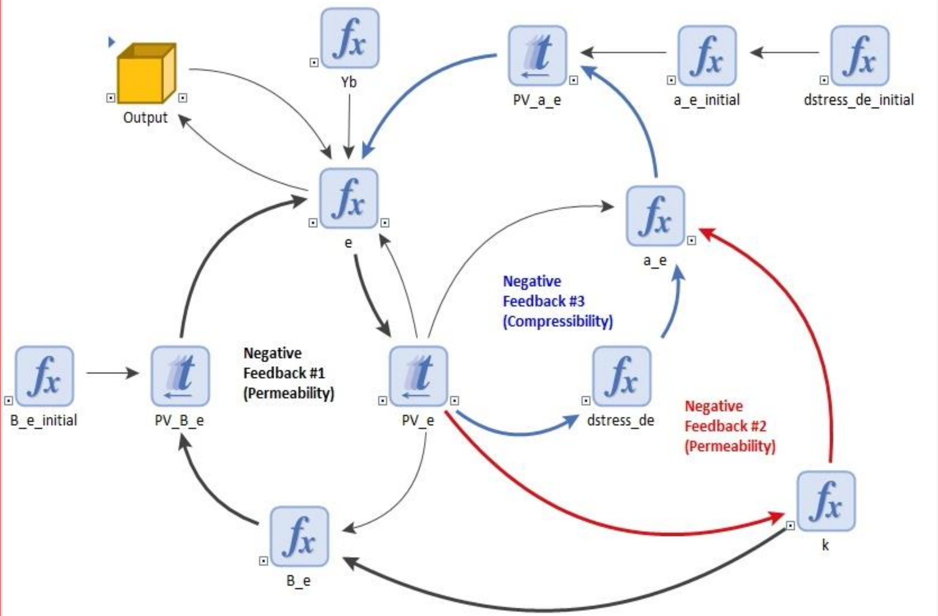
Spatial Feedback



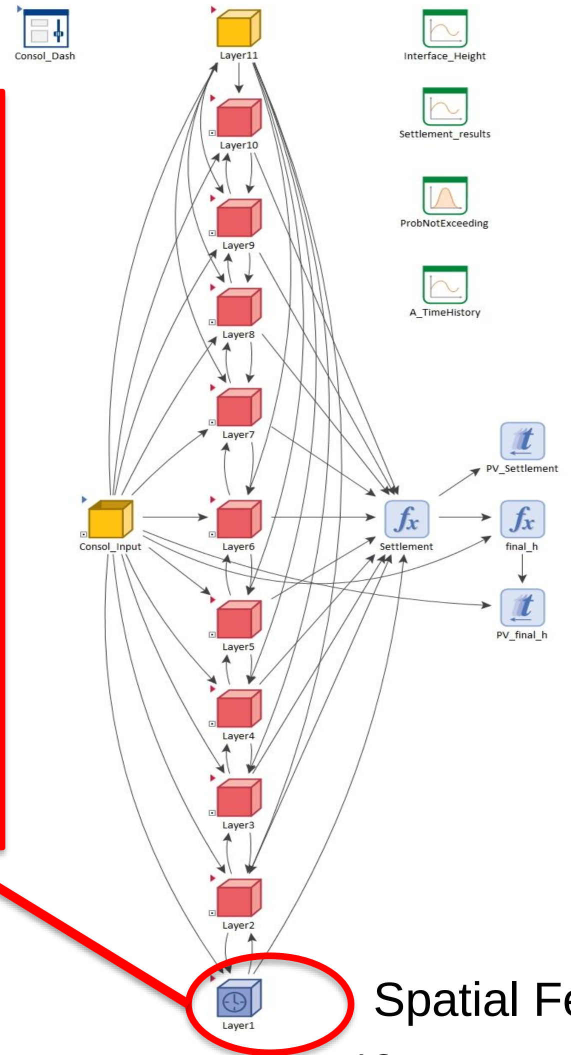
Boundary Condition: Single Drainage

Case Study – Consolidation SubModel

Inside GoldSim ……



Temporal Feedback

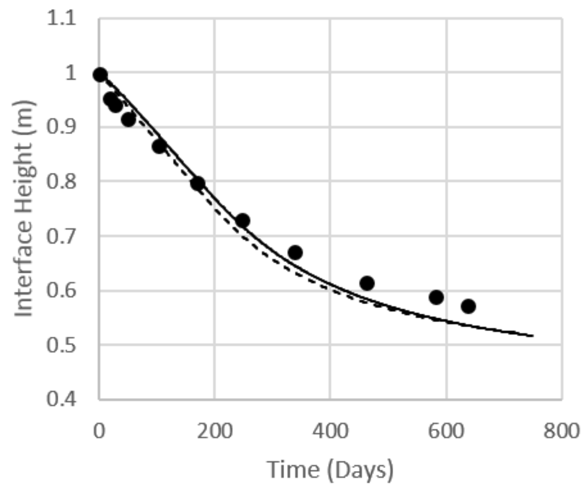


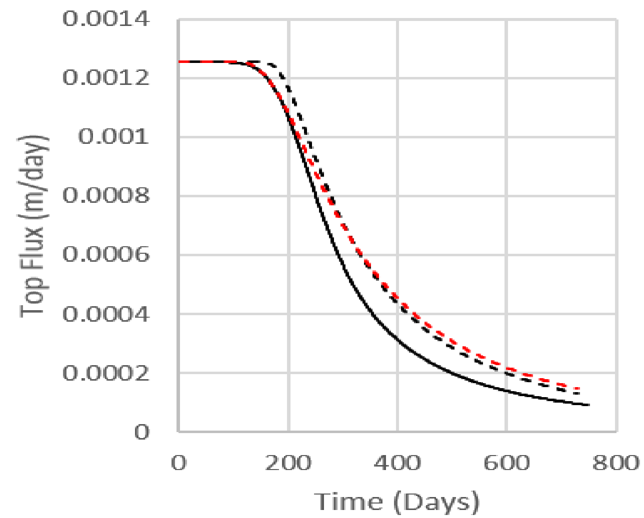
Spatial Feedback

See the GeoEdmonton 2018 conference paper for further details

Case Study – Consolidation Validation

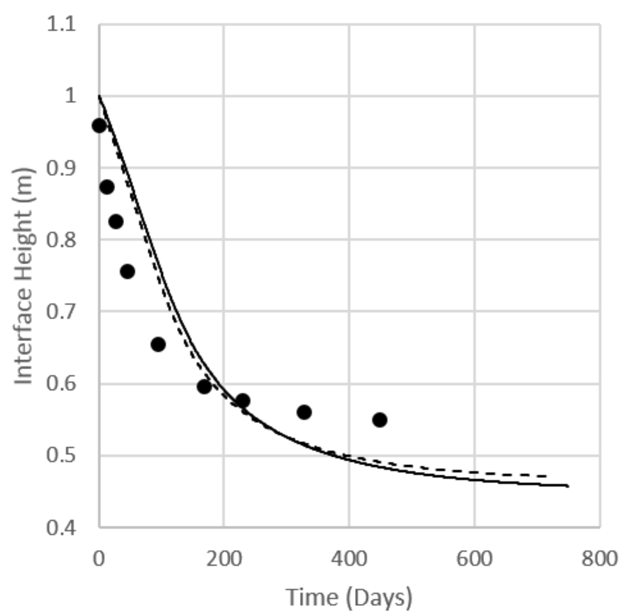
1 m Column
Caustic MFT

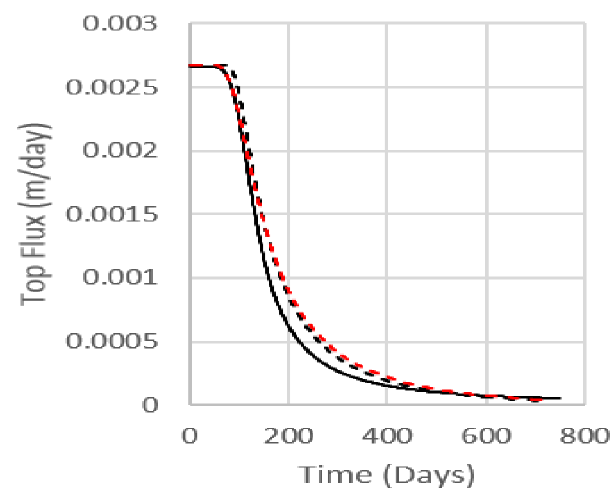




***Remember to include "Extreme Condition" in validation cases**

1 m Column
Non-Caustic MFT





Soil Water Dynamics of Tailings Cap

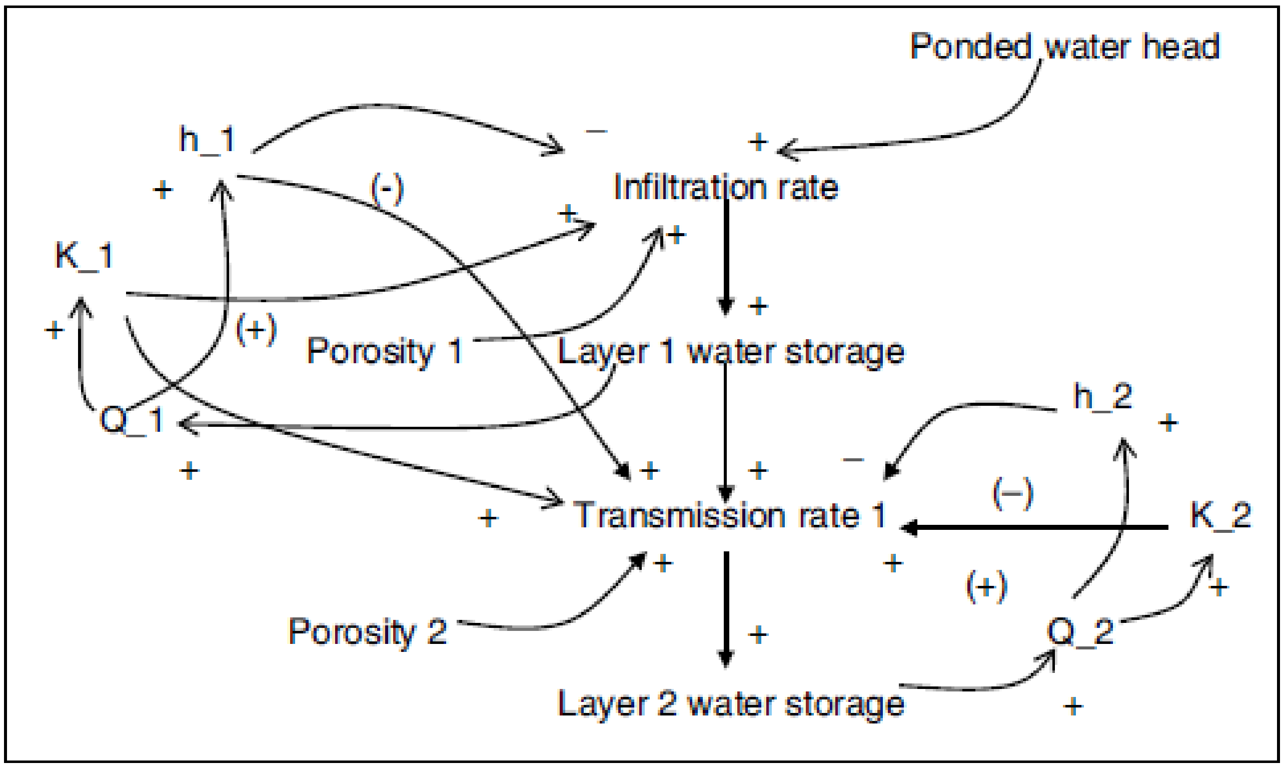
Part I: A Bottom-Up Re-Interpretation of Tailings Consolidation Flux using System Dynamics and Causal Loop Diagrams

Part II: Unsaturated Flow Interaction in Coarse Sand Tailings (CST) Cap

Case Study – Partial CLD for CST Cap

System dynamics modeling of infiltration and drainage in layered coarse soil

Mingbin Huang[1,3], Amin Elshorbagy[1,4], S. Lee Barbour[1], Julie D. Zettl[1], and Bing Cheng Si[2]



Partial Causal Loop Diagram (CLD)

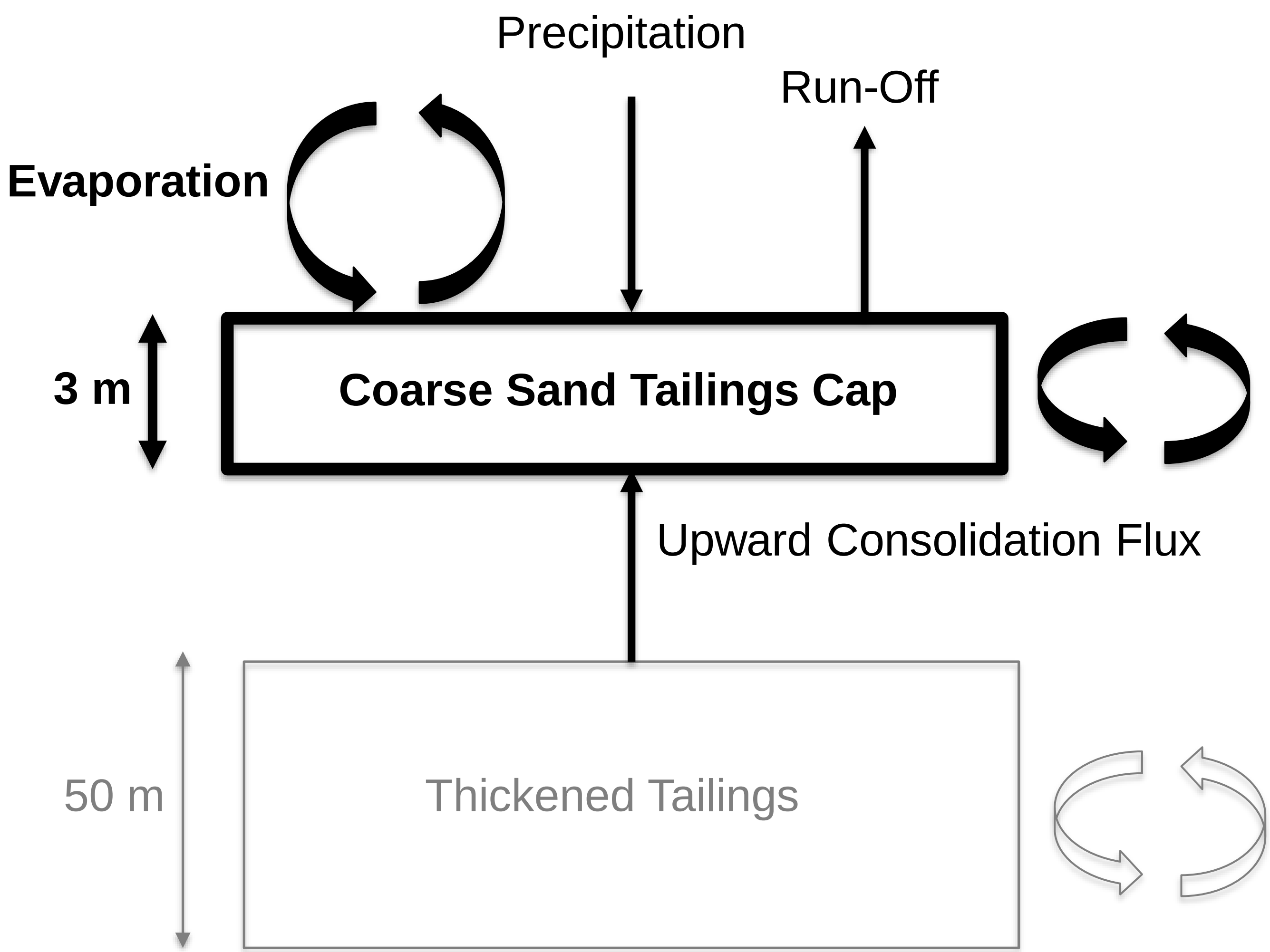
Assumptions

- Darcian Flow
- Advection-Dominated
- One-Dimensional
- No Volume Change

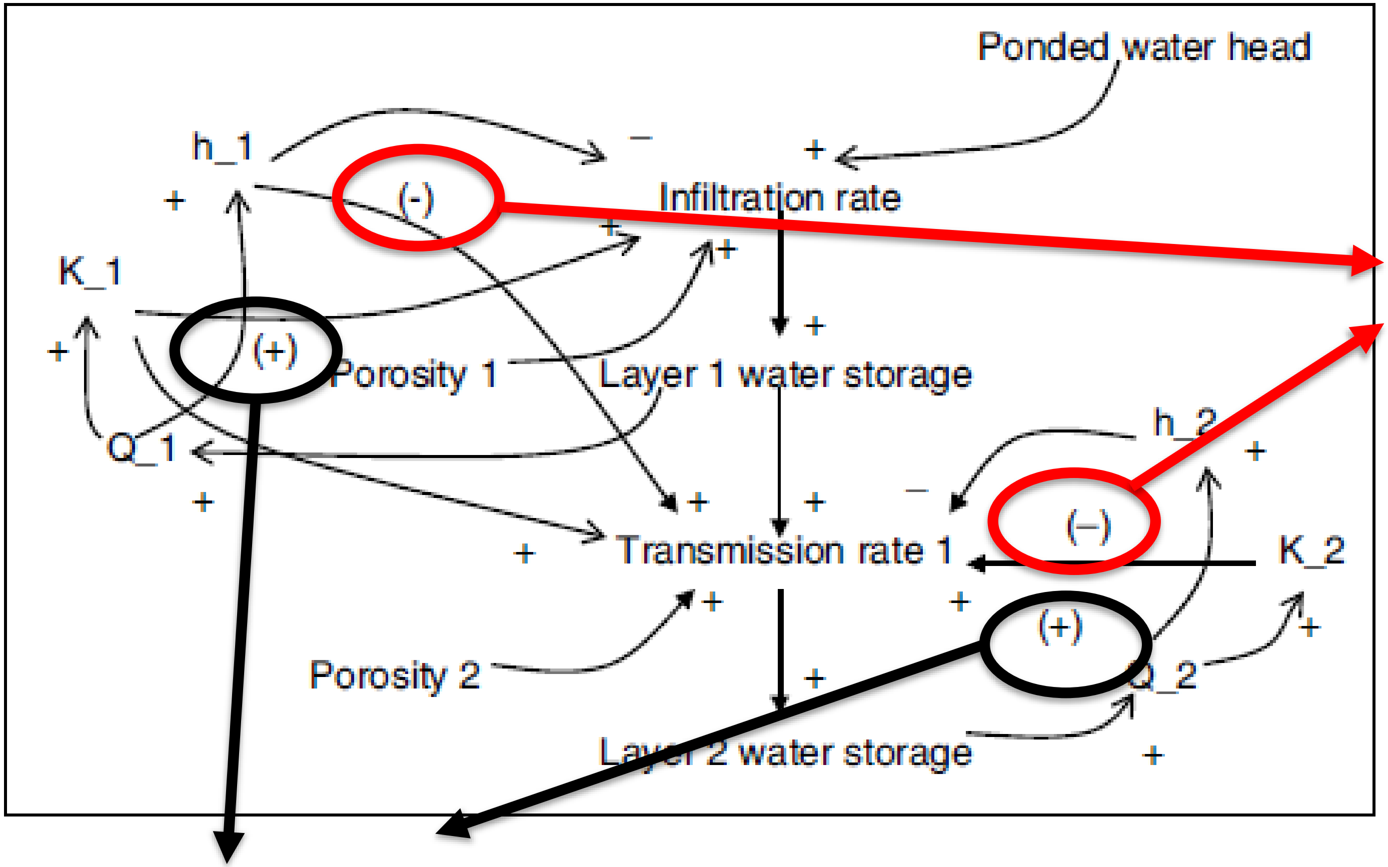
Key Deficiencies

- **No Climatic Input**
- **Limited Validation**
- ~~No Consolidation~~
- **Exogenous variables not shown in CLD**

Case Study – Simulation Setup



Case Study – Partial CLD for CST Cap



Negative (Balancing) Loop

- Suction-Driven
- Dominates when evaporation > precipitation

Positive (Reinforcing) Loop

- Infiltration-Saturation Driven
- Dominates when precipitation > evaporation

Case Study – CST Cap

The mathematics is hidden behind the one-way arrows

Vol Water Content

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

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

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

Van Ganutchen - Maulem 1980 and Richard's Equation (Darcy's Law)

Case Study – Evaporation CLD

Evaporation-Suction Model for Climatic Input

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

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

Wilson et al, 1997

Decompose $\Longrightarrow$ Causal Loop Diagram

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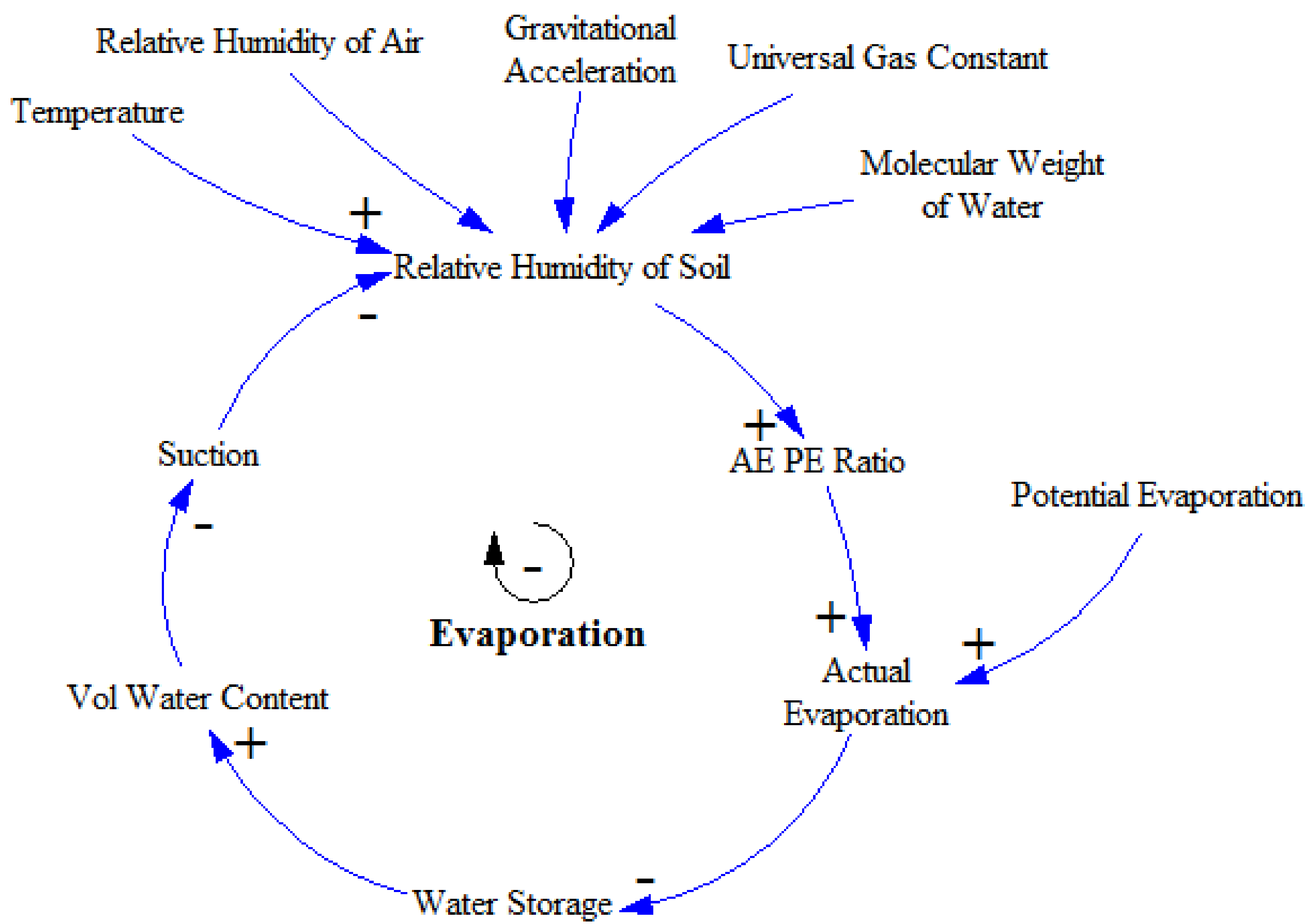
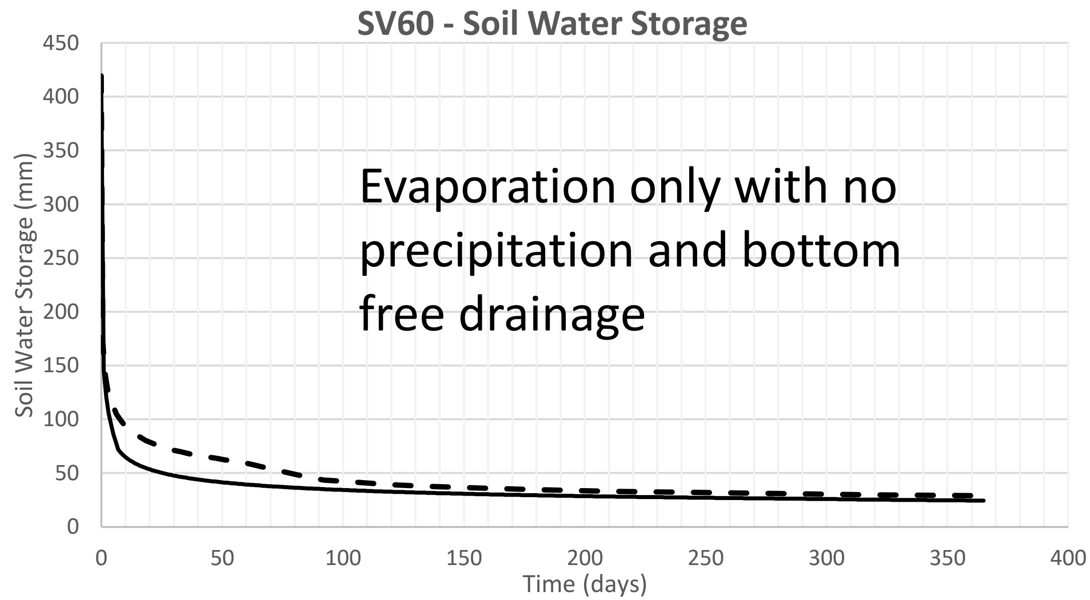
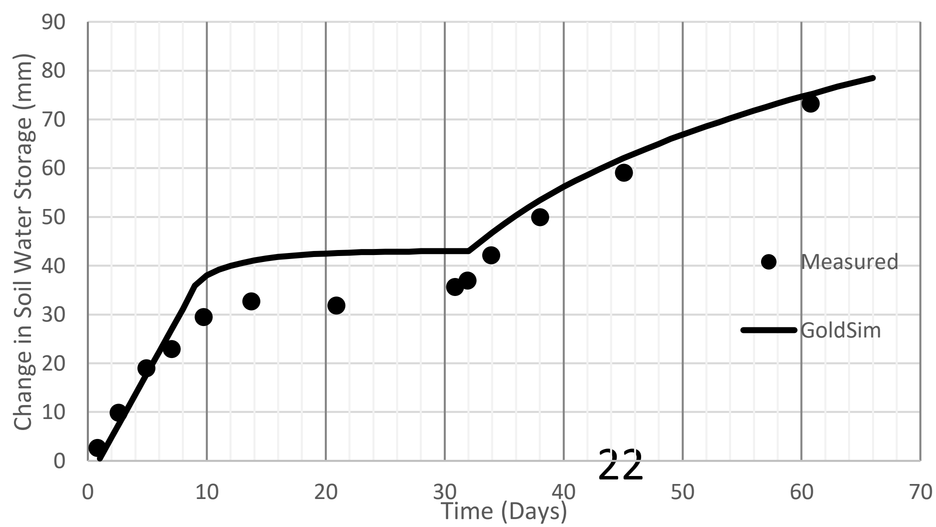
Case Study – Evaporation CLD



Case Study – Validation

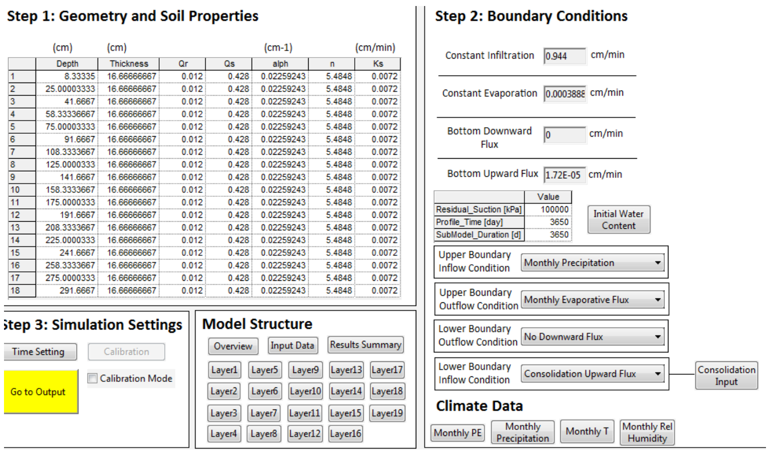


***Again, remember to include "Extreme Condition" in validation cases.**

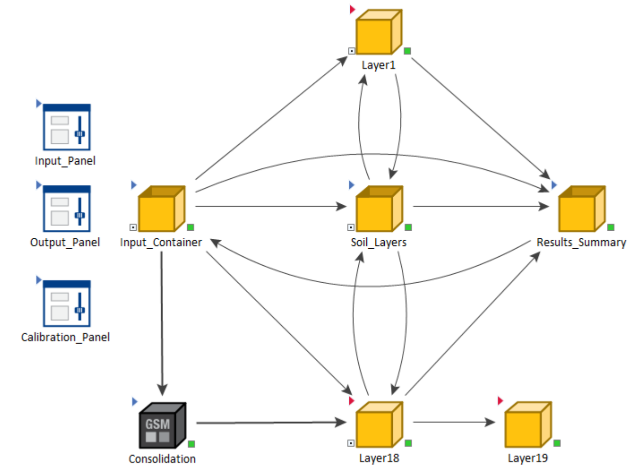


Silt column evaporation with constant head bottom boundary for the first 30 days

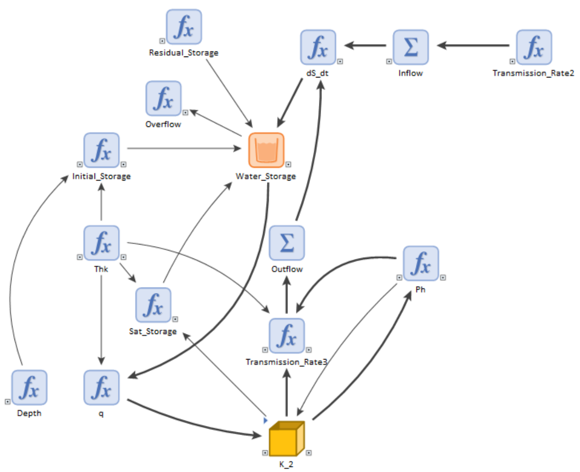
Case Study – Simulation Setup



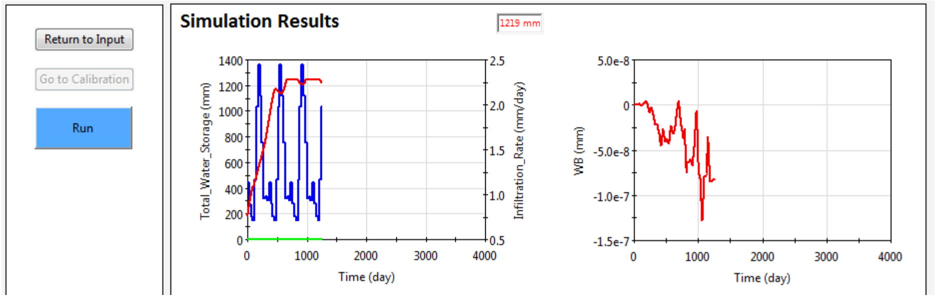
User Input



Model Overview

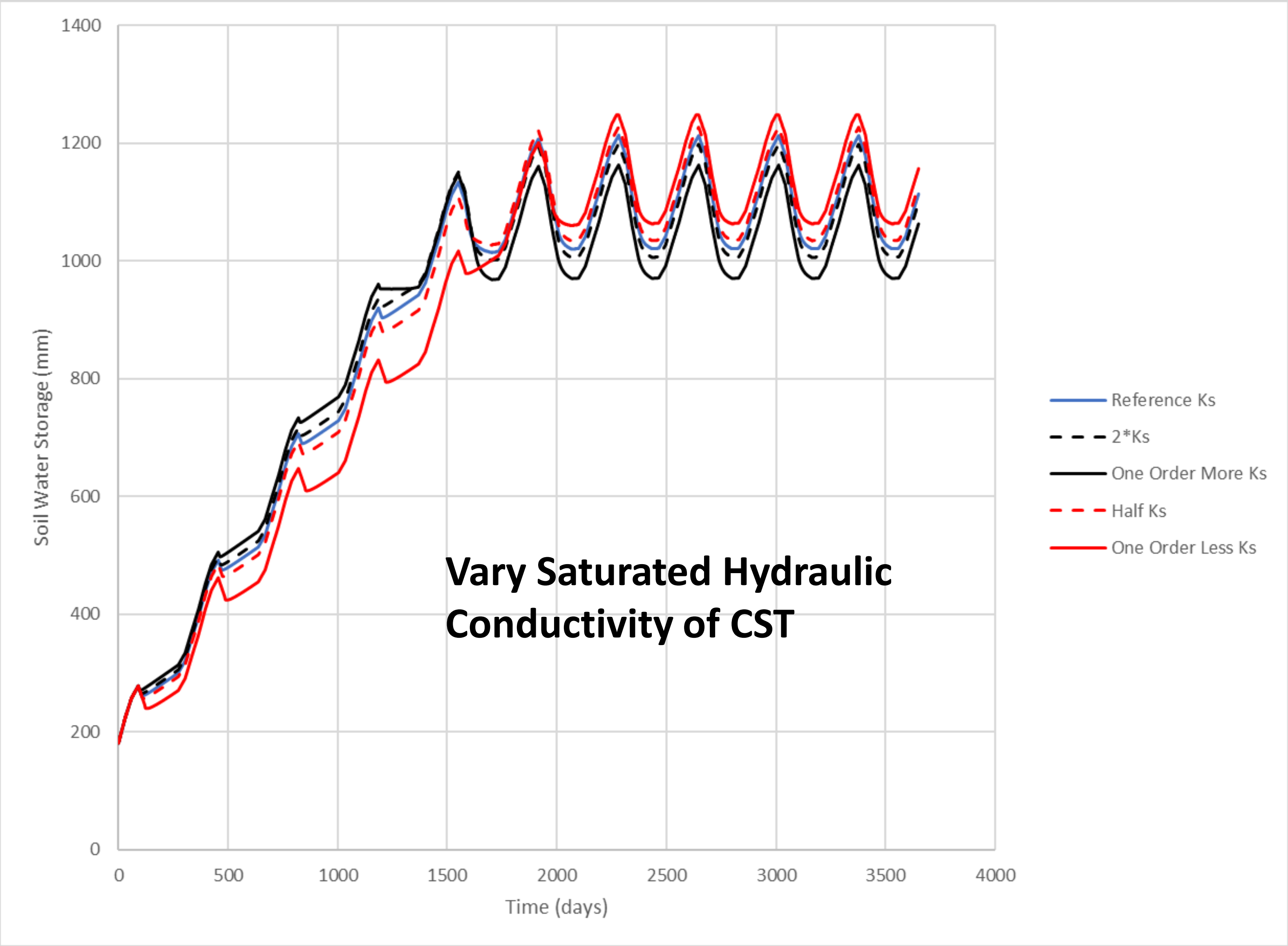


Layer Setup

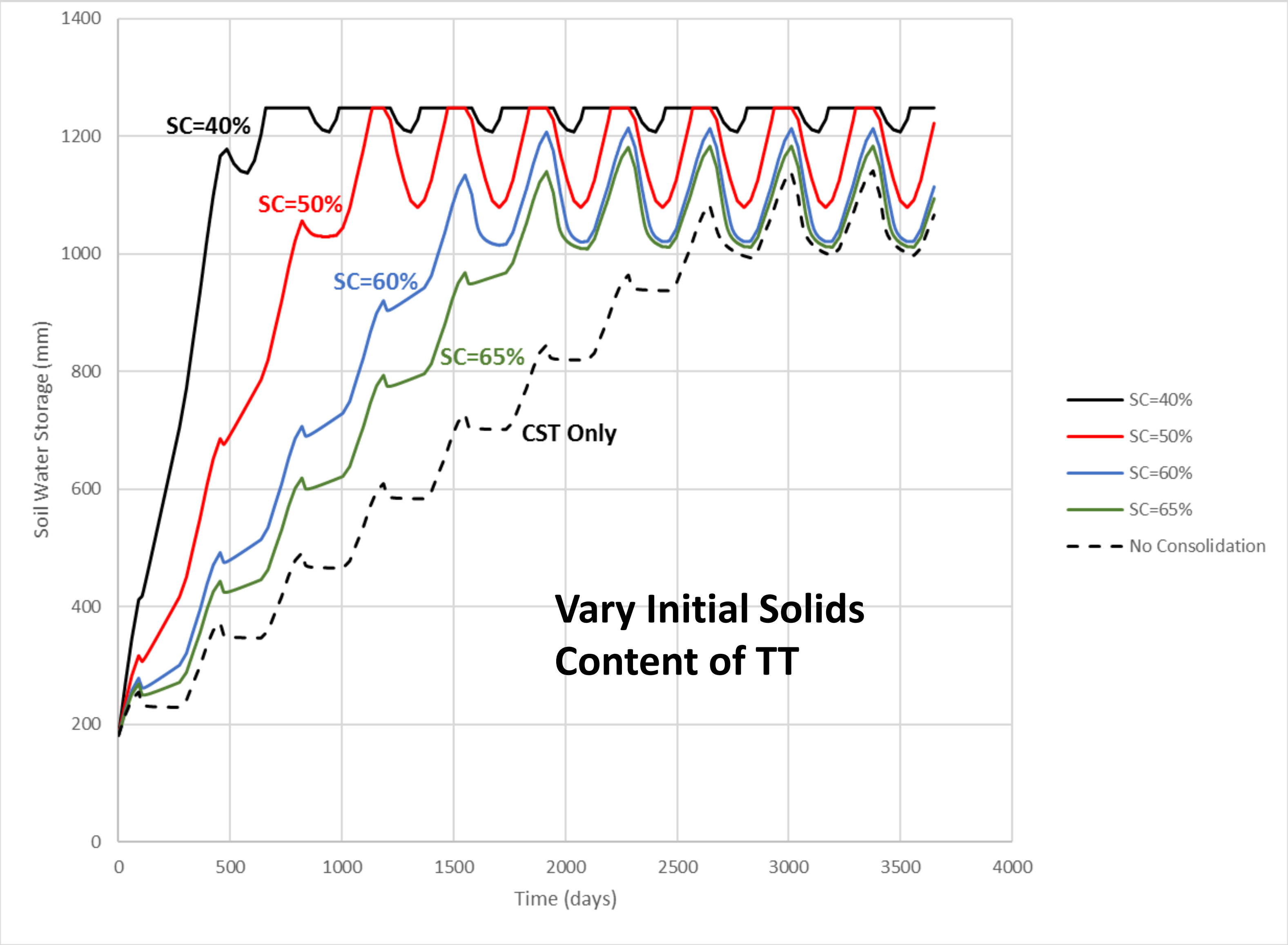


Real-Time Simulation Results

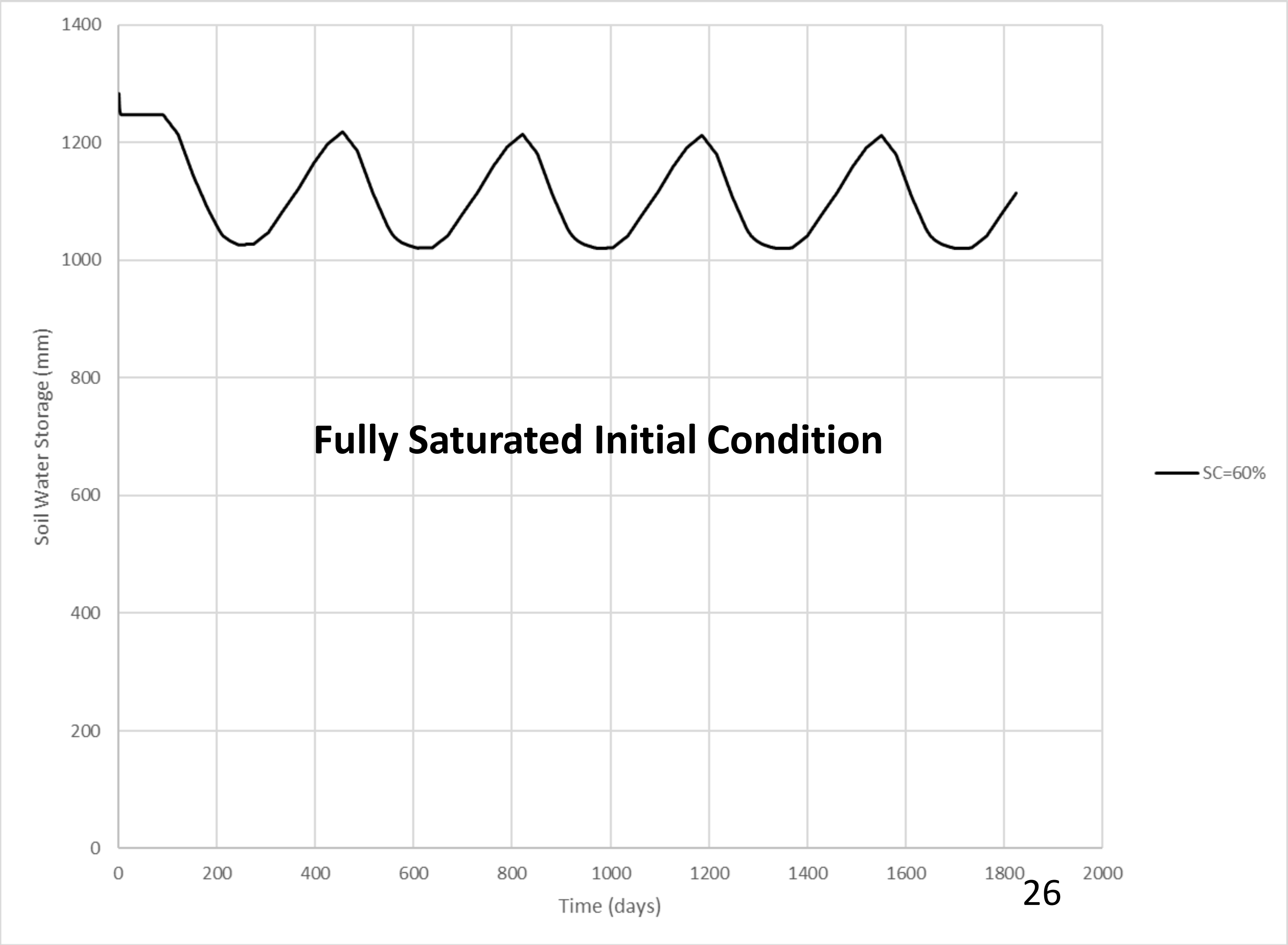
Case Study – Preliminary Results



Case Study – Preliminary Results



Case Study – Preliminary Results



Case Study

Question 1: When will the tailings cap reach a steady-state in terms of water storage?

Answers and Insights: *It varies from 2 years to 7 years depending on the upward flux from the consolidating TT.*

A 10% increase in the initial solids content of TT can delay the time to steady-state by 1 to 2 years. Above 60% solids content, the upward consolidation flux has little influence on "time to steady state".

Case Study

Question 2: What are the major factors that will influence the time to reach steady-state

Answers and Insights: *Upward consolidation flux from TT and initial saturation conditions of CST are two major factors; saturated Ks of the CST cap has little temporal influence.*

Incentives for improving initial solids content of TT above 65% may be minimal.

Concluding Remarks

- Why System Dynamics?
  - **Feedback Structures**
  - Transparency
  - **Rigorous Qualitative Process**
  - Scalability
  - **Participatory Modelling**
  - Structural Sensitivity
  - **Ability to model soft variables**
  - And many more

Concluding Remarks

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

Acknowledgements

- **Dr Nicholas Beier**

COSIA Canada's Oil Sands Innovation Alliance | Delivering Environmental Performance

Alberta Innovates Energy and Environment Solutions

NSERC CRSNG

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Vensim

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