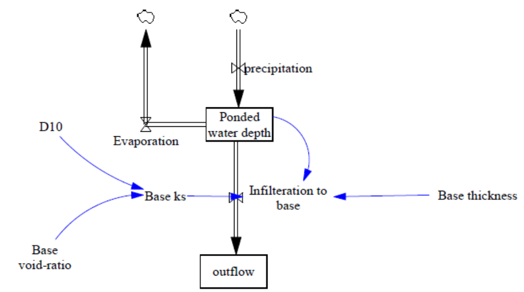
National Road Research Alliance

DEPARTMENT OF TRANSPORTATION



Mechanistic Load Restriction Decision Platform for Pavement Systems Prone to Moisture Variations

"A System Dynamics Simulation Framework"

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University of New Hampshire

Outline

1. Project Overview
2. System Dynamics Modeling (SDM)
3. SDM development
4. Hydrological Structure
5. Geotechnical Structure
6. Pavement Response Structure
7. Upcoming Tasks and Discussion

1. Project Overview

❑ Project Objectives

✓ Develop a mechanistic framework to improve robustness of the load restriction decision process.

✓ Improve post-flooding and seasonal pavement capacity assessment.

✓ Implement a flexible platform that incorporates multi-variant effects with forecasting capability.

System dynamics modeling and analysis

integrating climate forecasting, soil-moisture state, pavement mechanics and traffic spectrum

✓ Develop a toolkit validated using field data for load restriction decision, specially for post-flooding load closures and openings.

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1. Project Overview
2. System Dynamics Modeling (SDM)
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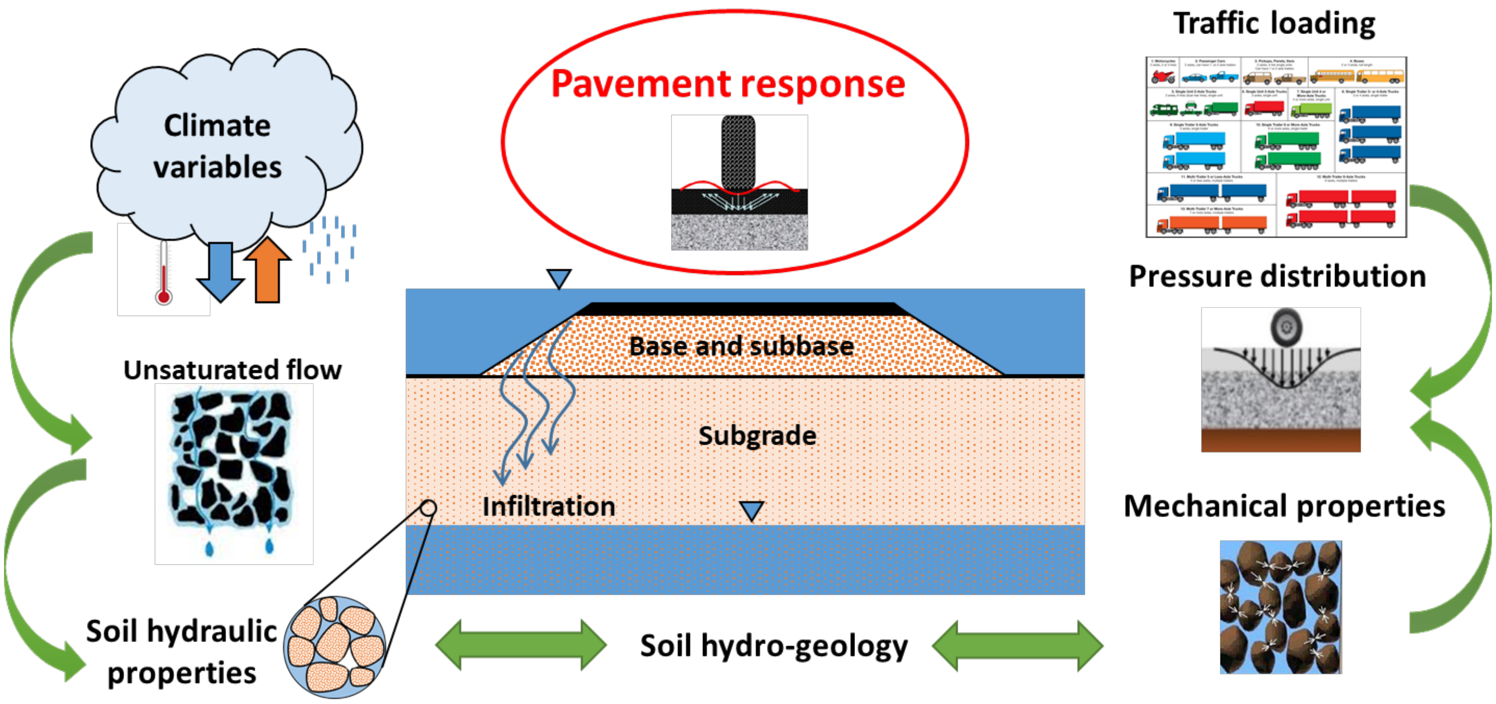
2. System Dynamics Modeling (1/8)

❑ What is system dynamics modeling?

An approach to study and manage complex systems (*includes multiple structures and components*) that change over time.



2. System Dynamics Modeling (1/8)

❑ What is system dynamics modeling?

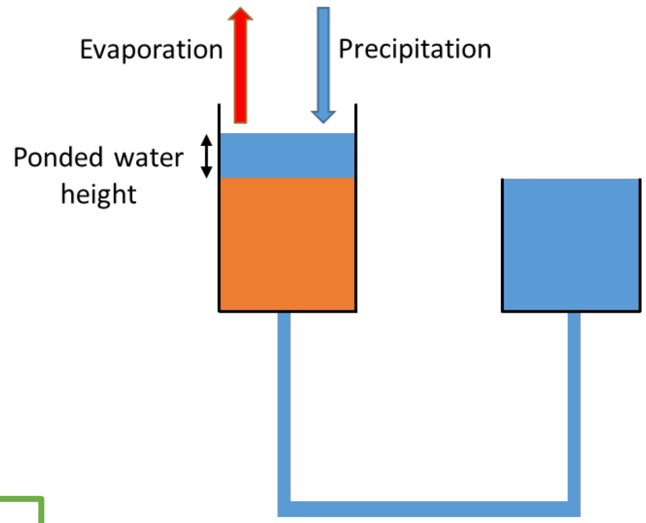
An approach to study and manage complex systems (*includes multiple structures and components*) that change over time.

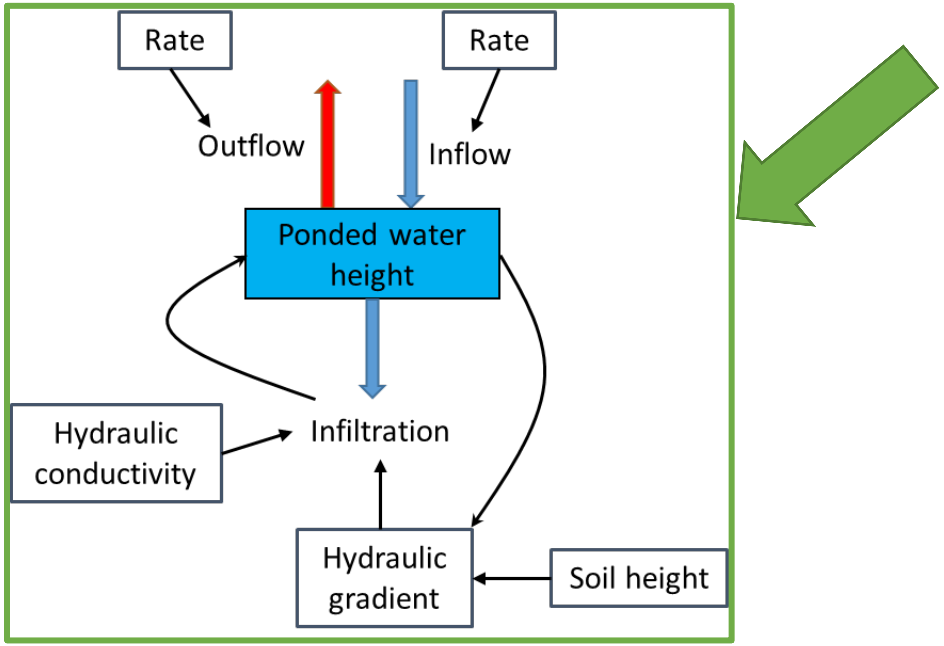
- ✓ Quantitative and qualitative (visual) assessment
- ✓ Identify interactions among system structures
  - ✓ Structures → Subset of a system (e.g., hydrological analysis)
- ✓ Real time coupled modeling (e.g., hydraulic and mechanical behavior)
- ✓ Can be formulated in computer software (e.g., Vensim Pro® in this research)

2. System Dynamics Modeling (2/8)

❑ Basic components

- ✓ Stock/level Variable
- ✓ Flow Variable
- ✓ Information Variable

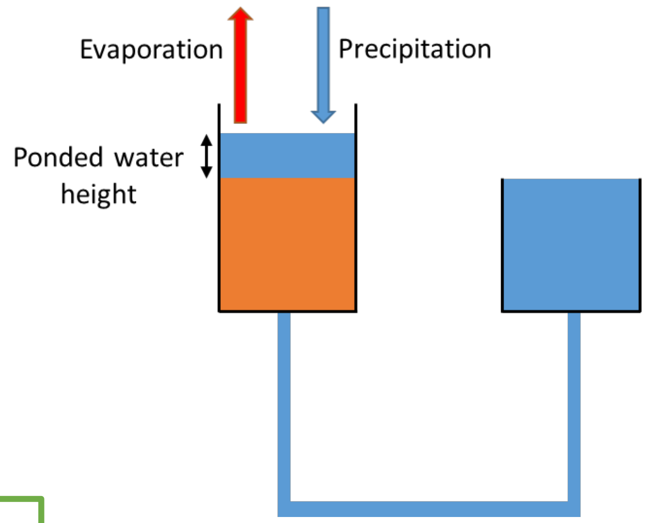


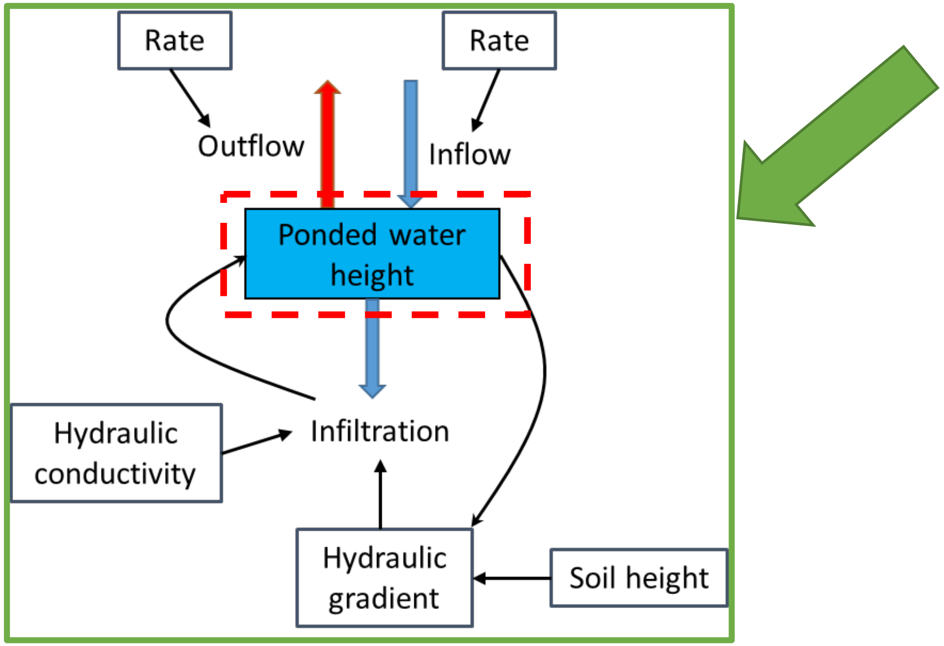


2. System Dynamics Modeling (3/8)

❑ Basic components

- ✓ Stock/level Variable
- ✓ Flow Variable
- ✓ Information Variable

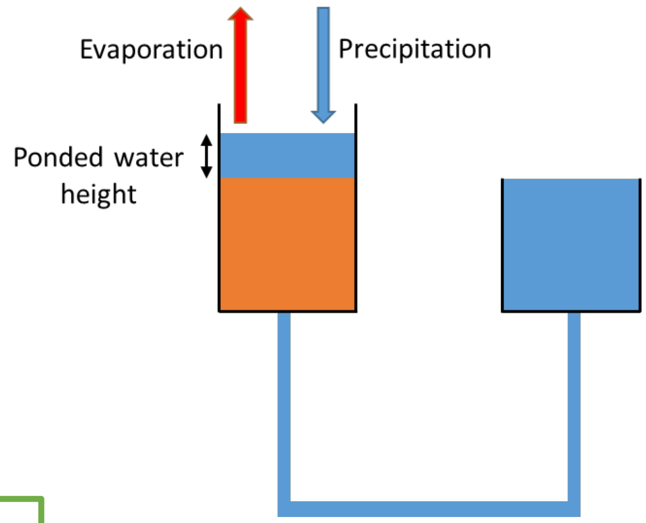


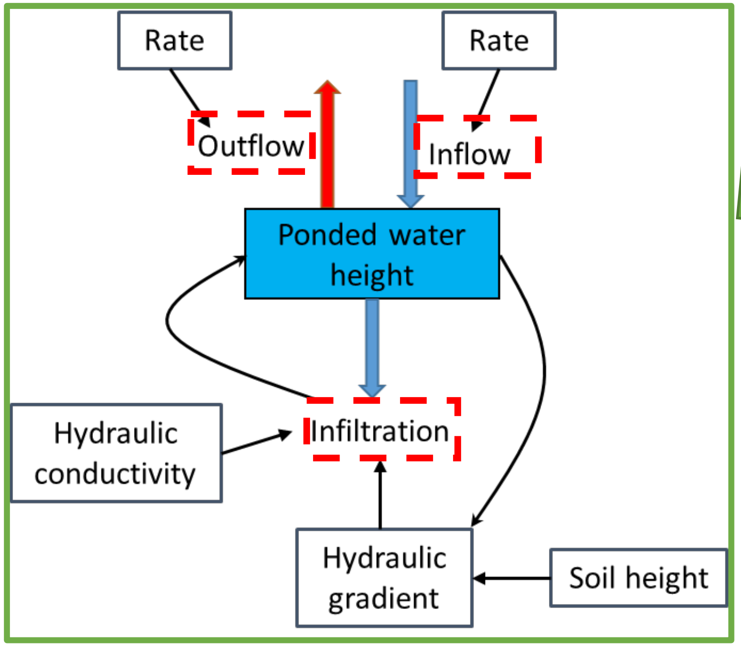


2. System Dynamics Modeling (4/8)

❑ Basic components

- ✓ Stock/level Variable
- ✓ Flow Variable
- ✓ Information Variable

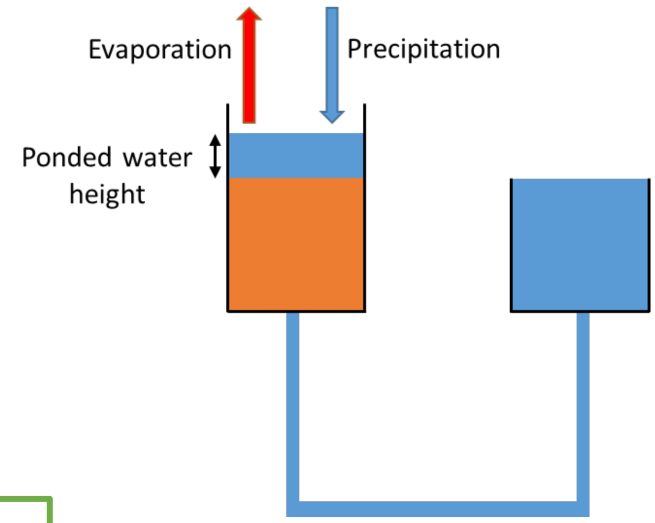


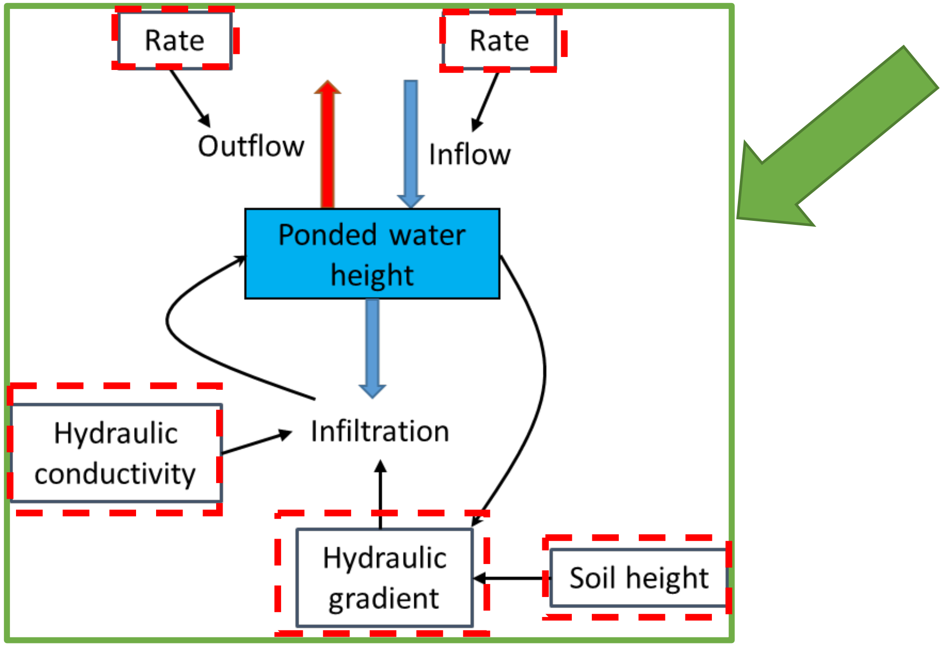


2. System Dynamics Modeling (5/8)

❑ Basic components

- ✓ Stock/level Variable
- ✓ Flow Variable
- ✓ Information Variable

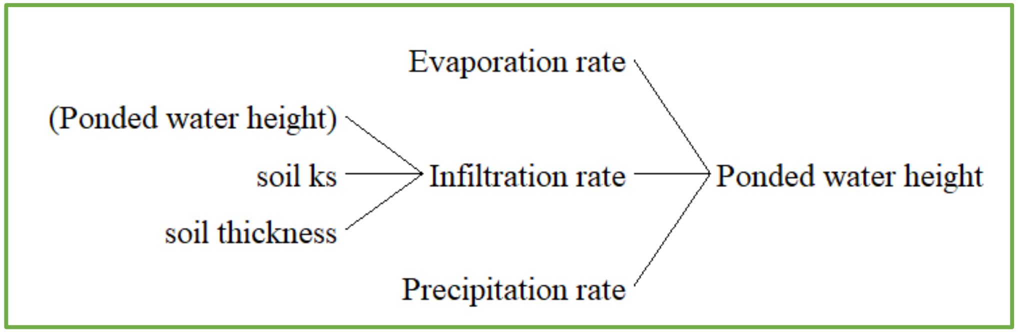


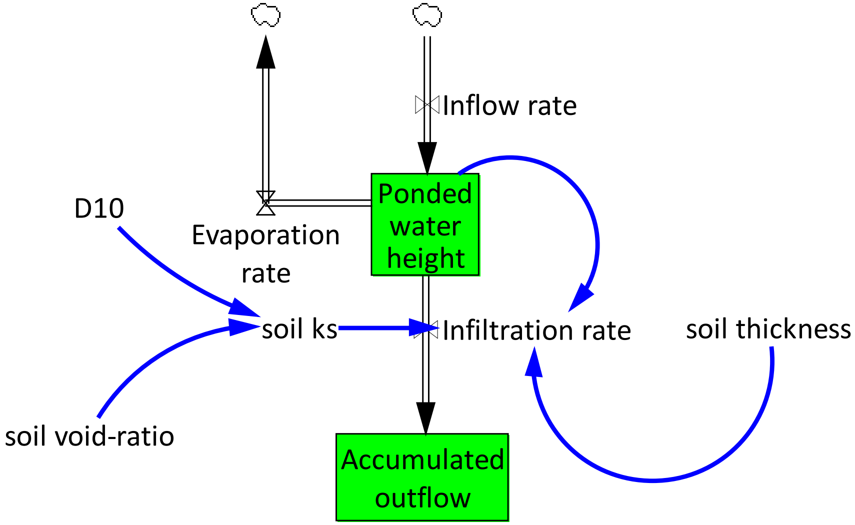


2. System Dynamics Modeling (6/8)

❑ Capabilities of SDM using computer tools:

1) Visualize interrelationship between variables
2) Diagrams of causes and uses
3) Functions (IF THEN ELSE, etc.)

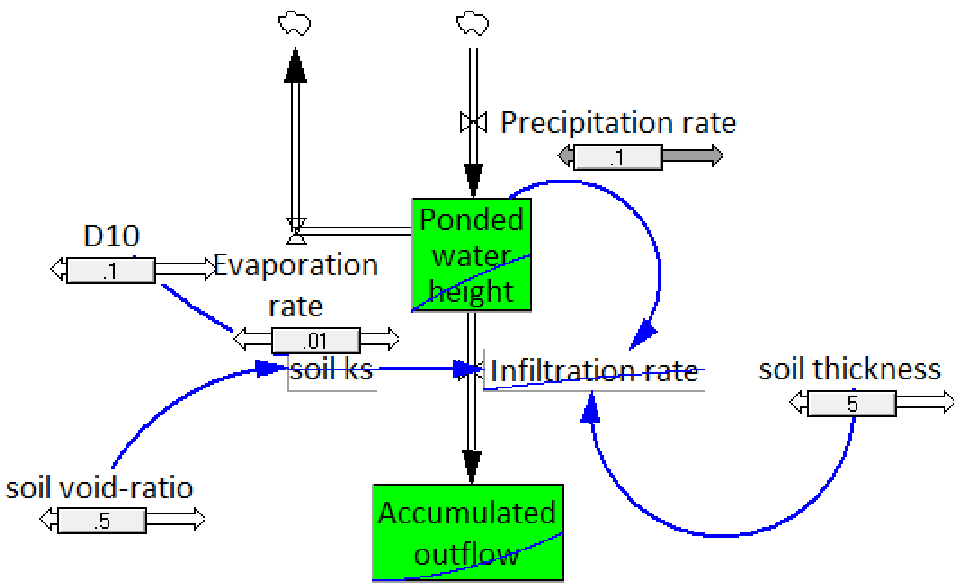


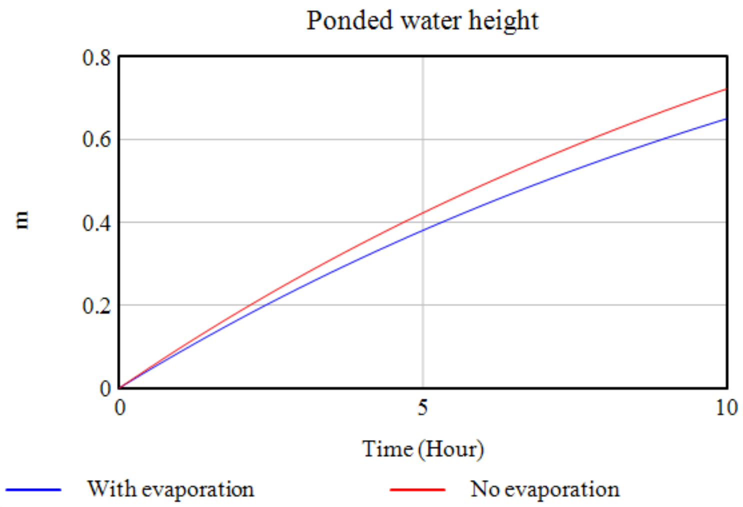


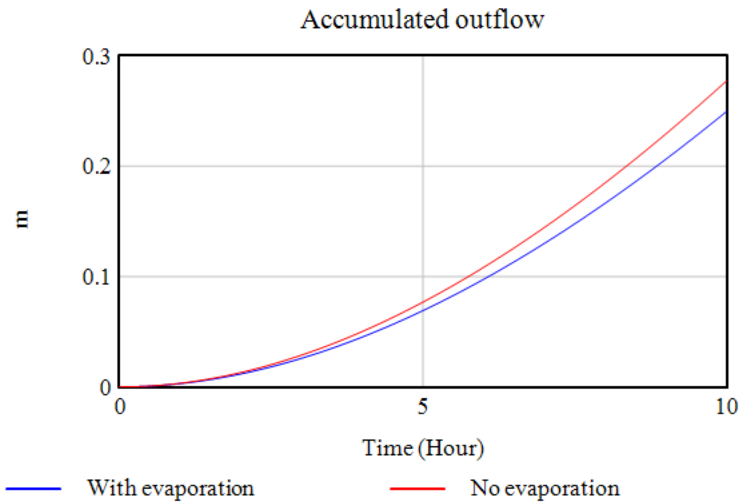
2. System Dynamics Modeling (7/8)

4) Simulation and Analysis

- ✓ Visualize the simulation results
- ✓ Simultaneous simulation of different scenarios and models







2. System Dynamics Modeling (8/8)

5) Data Use

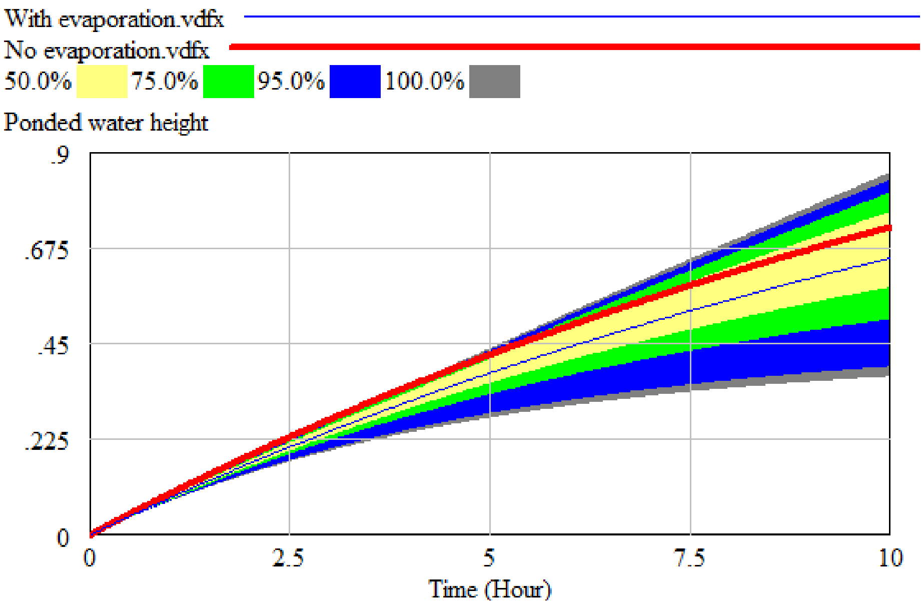
✓ Different forms of data: time series, data with missing values, subjective data.

6) Sensitivity Testing

✓ Monte-Carlo multivariate sensitivity simulations

Example:

Sensitivity of ponded water height to effective grain size (D_{10}) and void ratio (multivariant effect)



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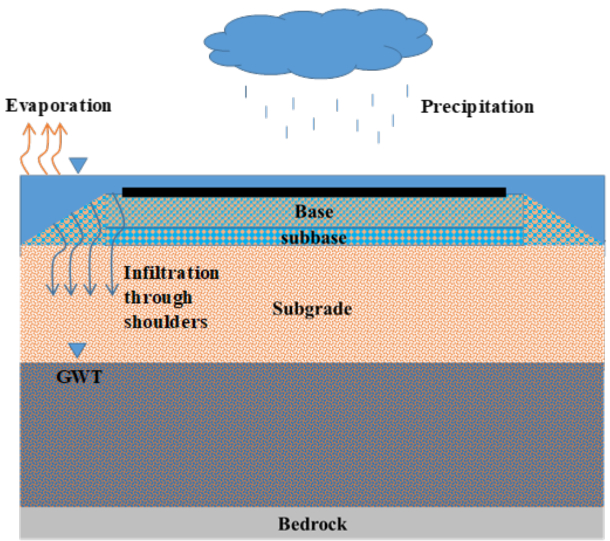
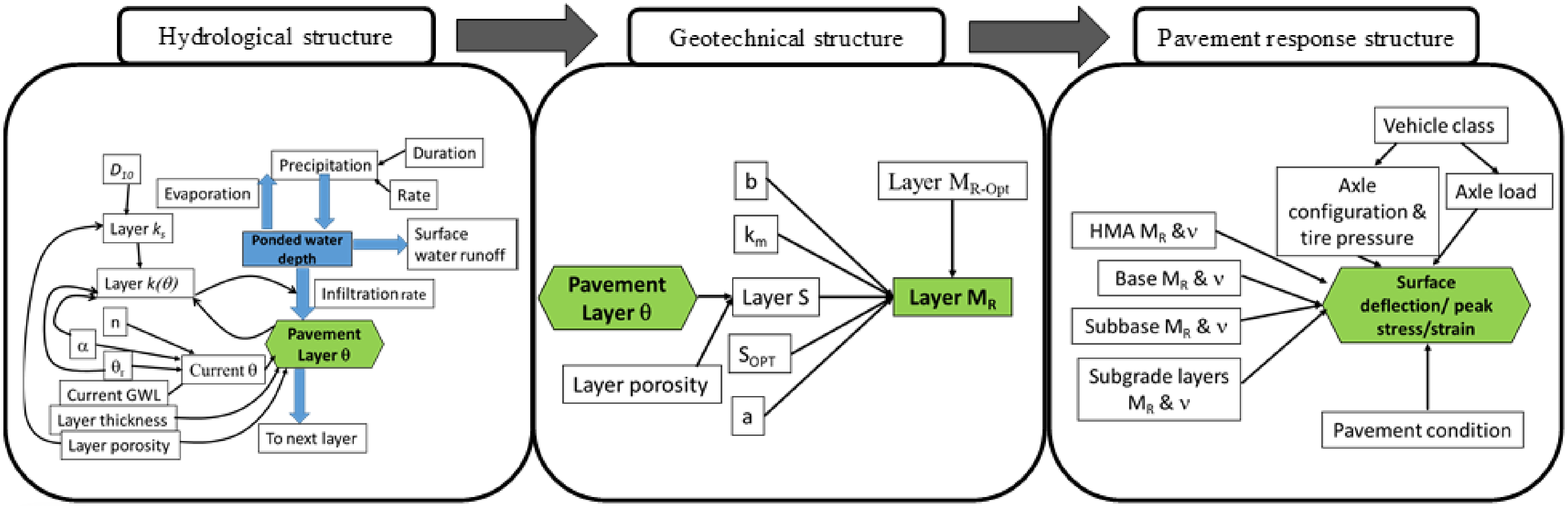
3. SDM development (1/2)

❑ System dynamics main structures

- ✓ Hydrological structure
- ✓ Geotechnical structure
- ✓ Pavement response structure



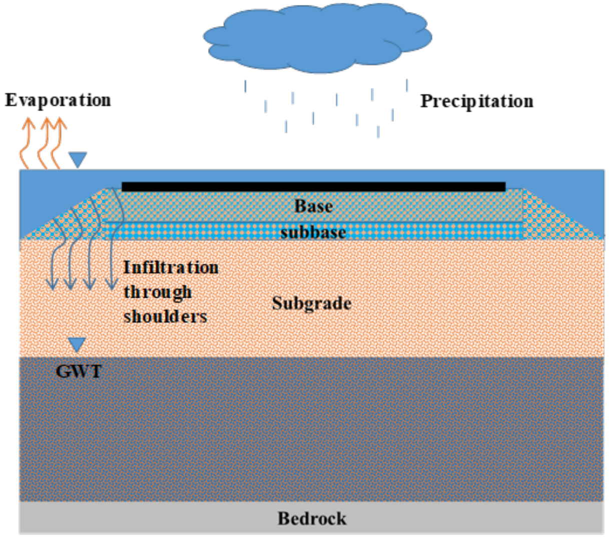


3. SDM development (2/2)

❑ Conventional flexible pavement example

✓ The SDM is discussed using example of a conventional flexible pavement system under moisture variations for 60 hours:

Variable	Value
AC layer thickness	0.1 m (~4 inch)
Base layer thickness	0.3 m (~12 inch)
Subbase layer thickness	0.1 m (~4 inch)
GWT depth (from subgrade surface)	2 m (~6.6 ft)
Subgrade sublayers height (10 layers)	0.2 m (~8 inch)
Bedrock depth	10 m (~32.8 ft)



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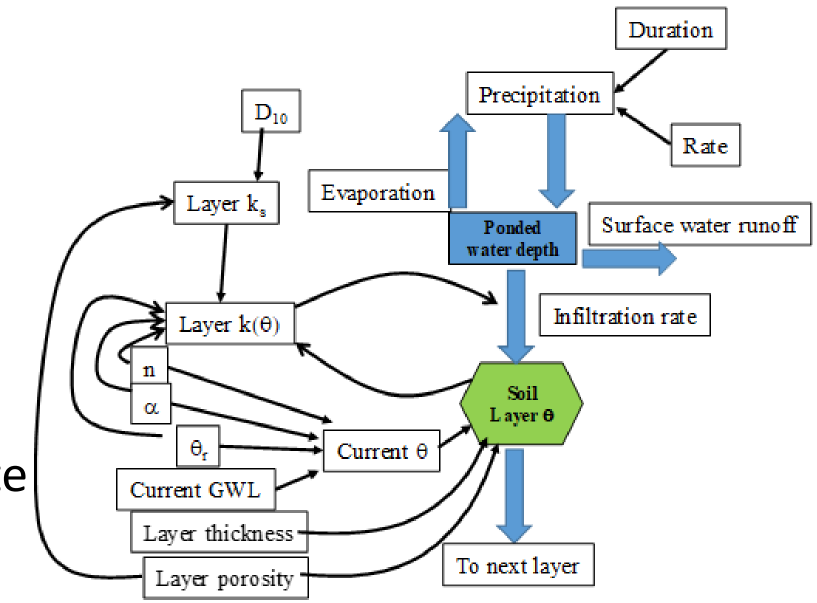
4. Hydrological Structure (1/15)

❑ Main components:

1. Climate information:

- Ponded water height
- Precipitation and evaporation rate

Forecasted climate data or average hourly rate



2. Unsaturated soil flow analysis:

- Initial soil moisture profile using van Genuchten (1980) SWRC and initial ground water depth:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha h)^{n_{vG}}}\right]^{m_{vG}}$$

- Moisture-dependent hydraulic conductivity

$$K(\theta) = K_{sat}\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{0.5}\left[1 - \left(1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{m_{vG}}}\right)^{m_{vG}}\right]^2$$

- Moisture movement analysis by numerical integration of Richard (1931)'s equations in discretized depth

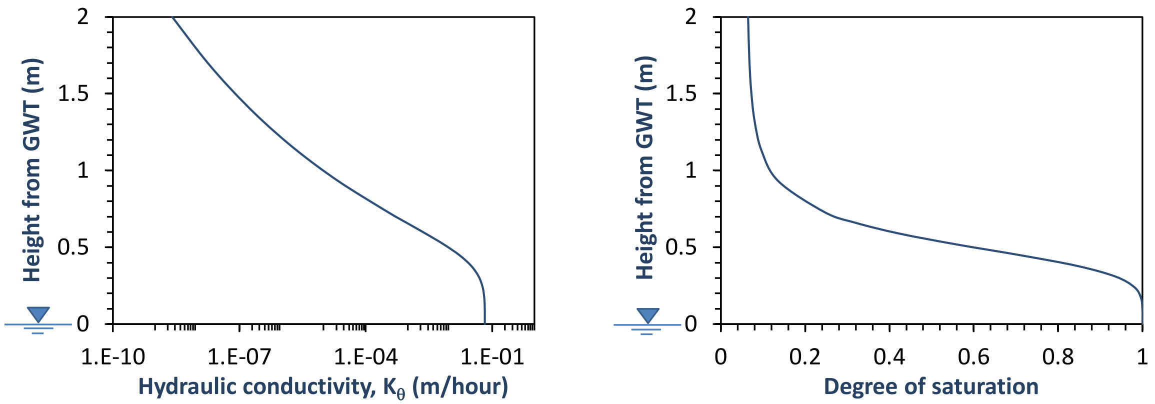
$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K_{(\theta)}\left(\frac{\delta h}{\delta z} + 1\right)\right]$$

❑ Flexible pavement example:

Material properties used in example

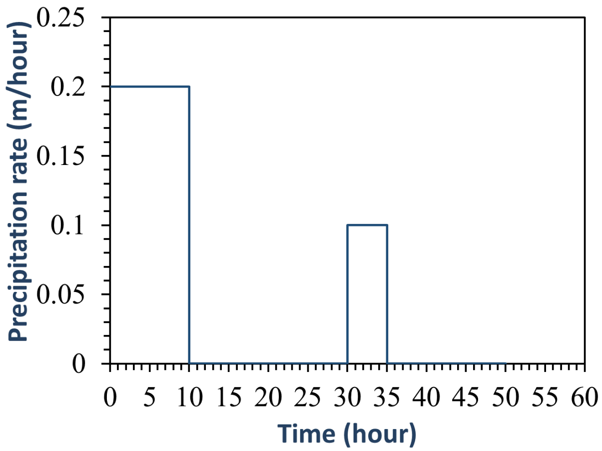
Properties	Attributes/Value
Soil type	Silty sand
Void ratio (e)	0.5
Effective grain size (D_{10})	0.035 (mm)
n_{vG}	5
a_{vG}	2
Residual volumetric water content (θ_r)	0.02
Saturated water content (θ_s)	0.3

Initial moisture and hydraulic conductivity profiles



Assumed climate condition in example

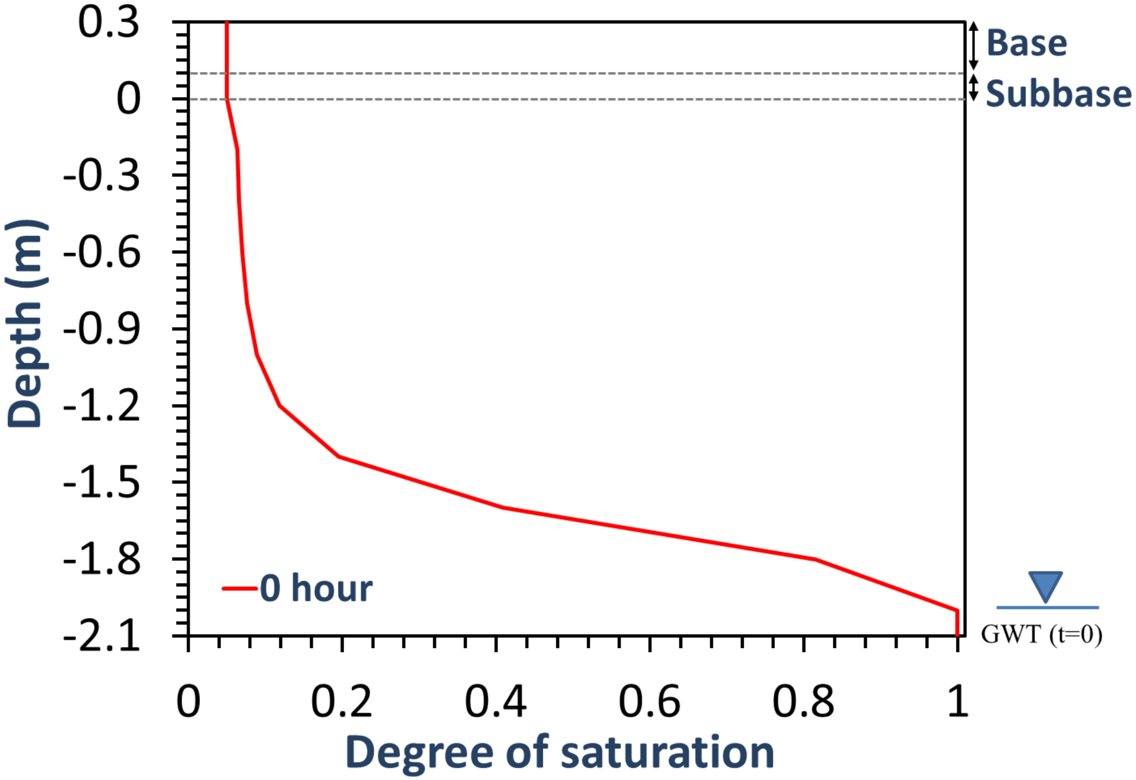
- ✓ Two periods of precipitation
- ✓ No evaporation and surface runoff

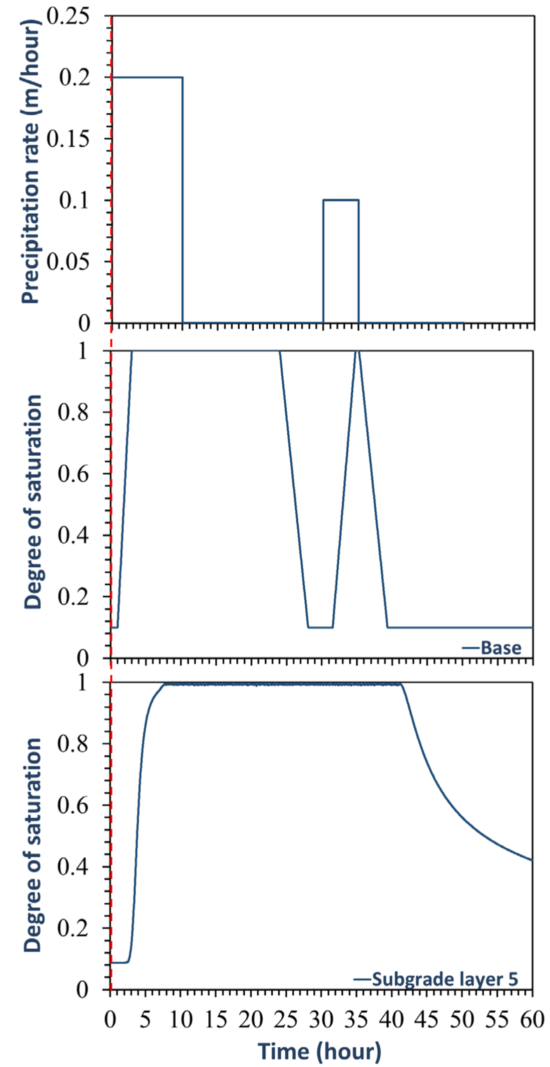


4. Hydrological Structure (3/15)

❑ Water movement simulation using the SDM

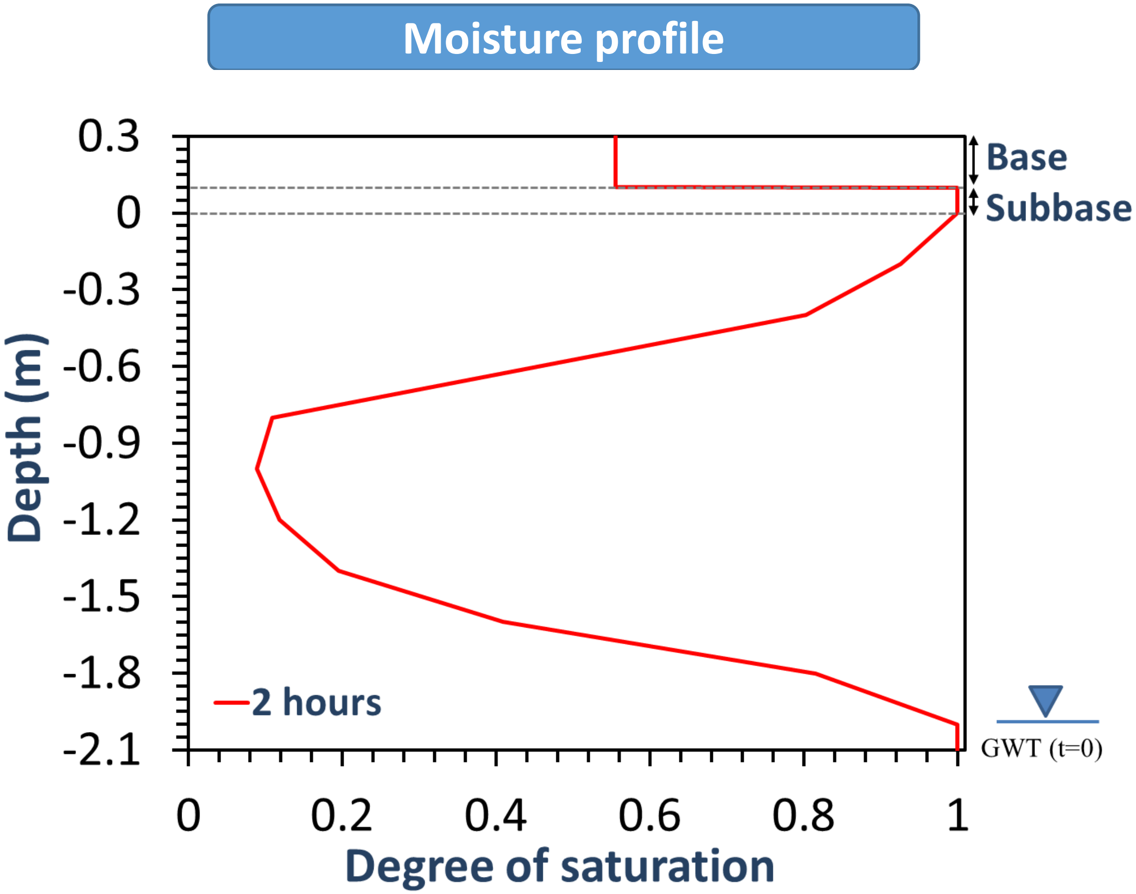
Moisture profile

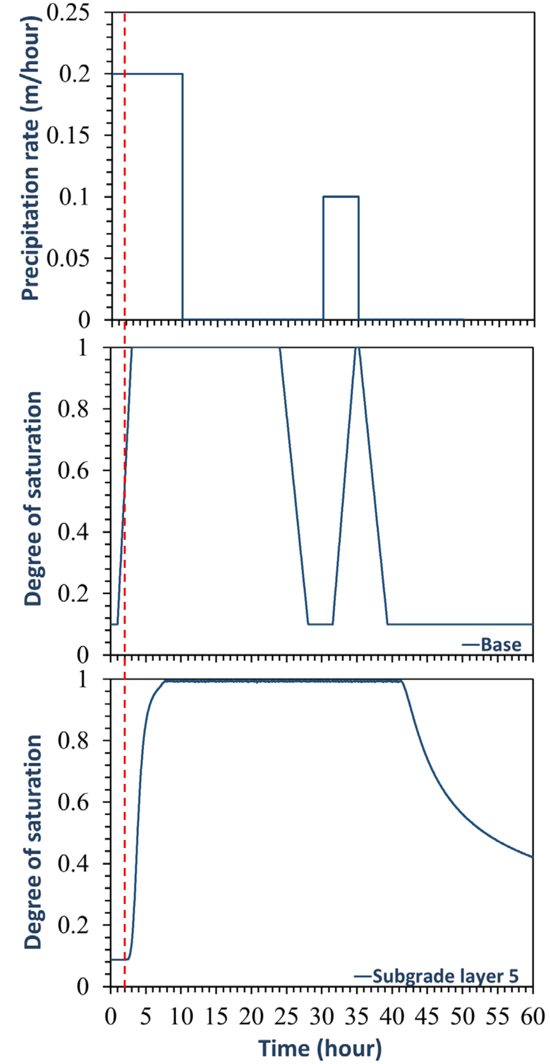




4. Hydrological Structure (4/15)

❑ Water movement simulation using the SDM

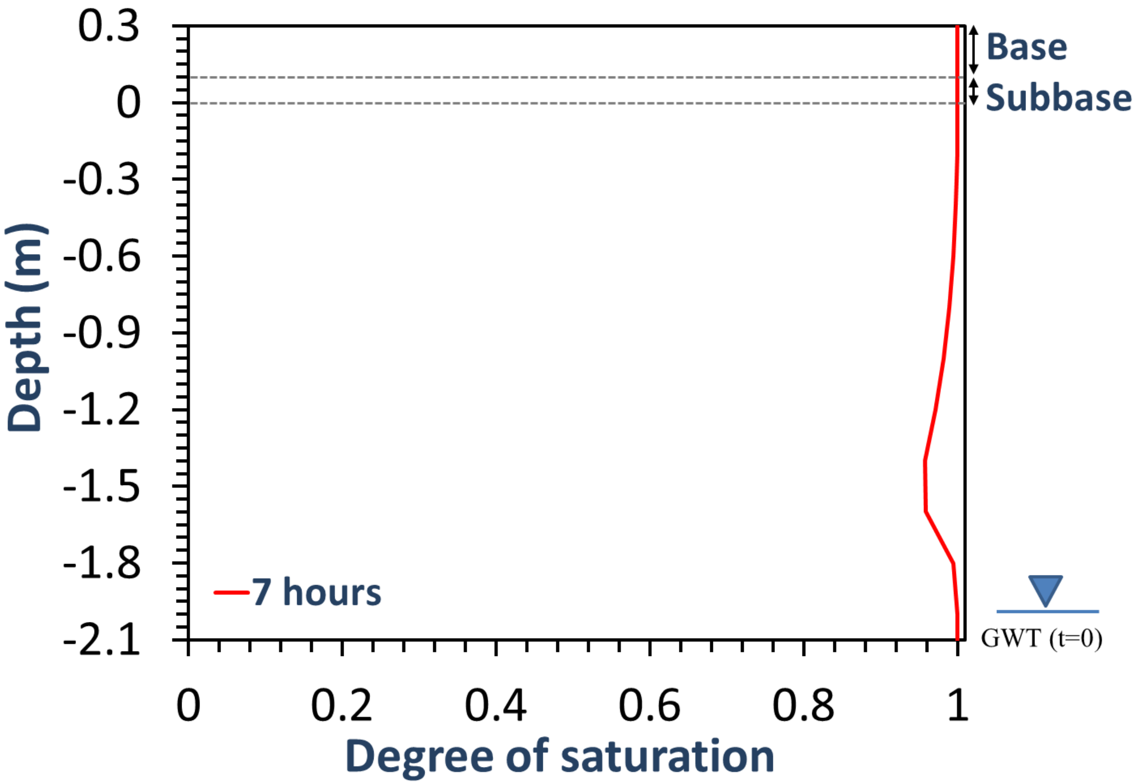


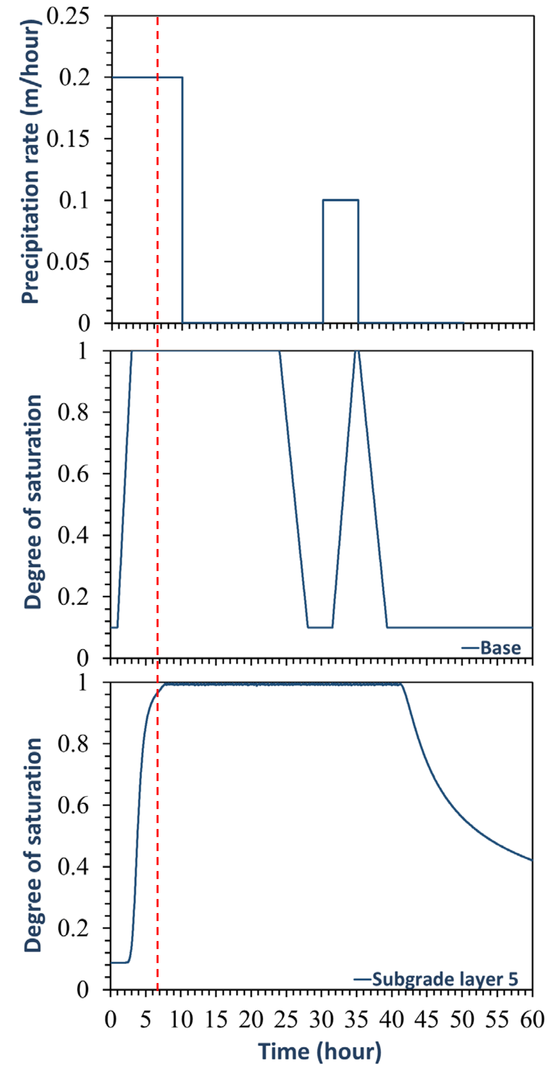


4. Hydrological Structure (5/15)

❑ Water movement simulation using the SDM

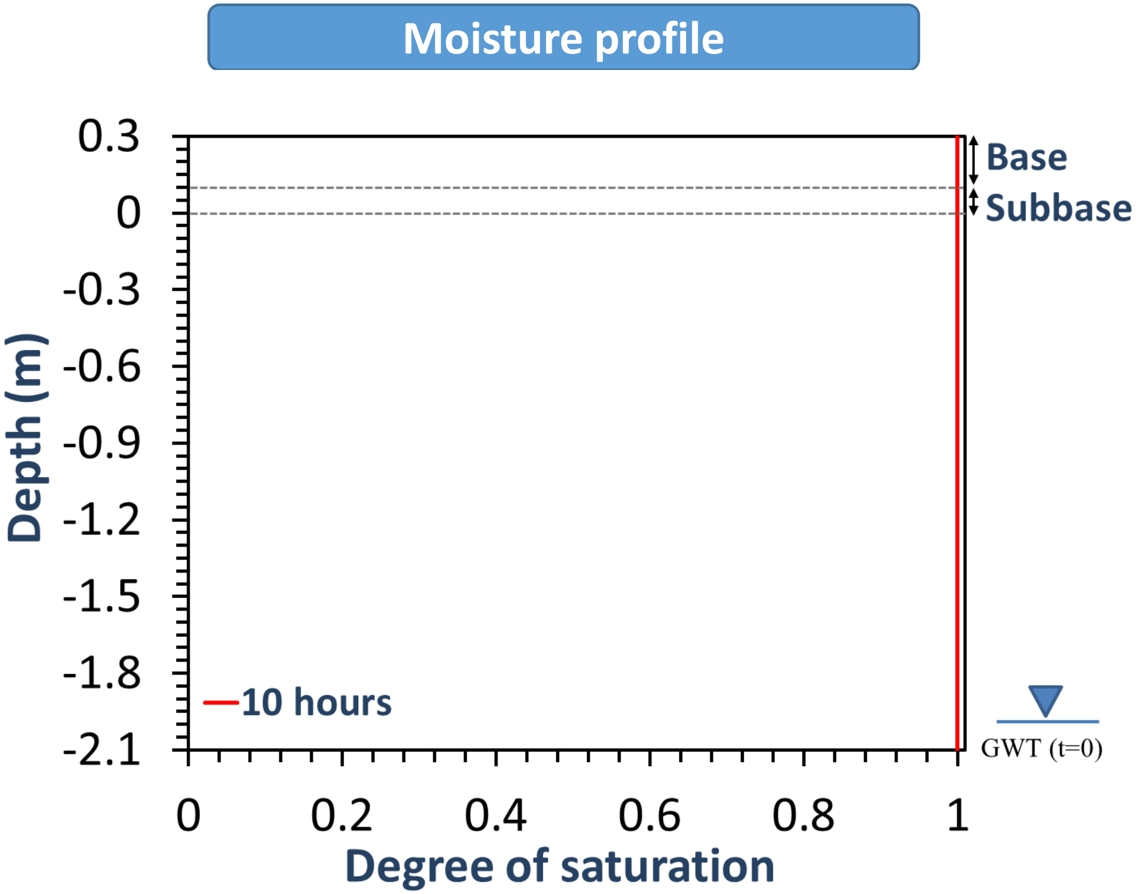
Moisture profile

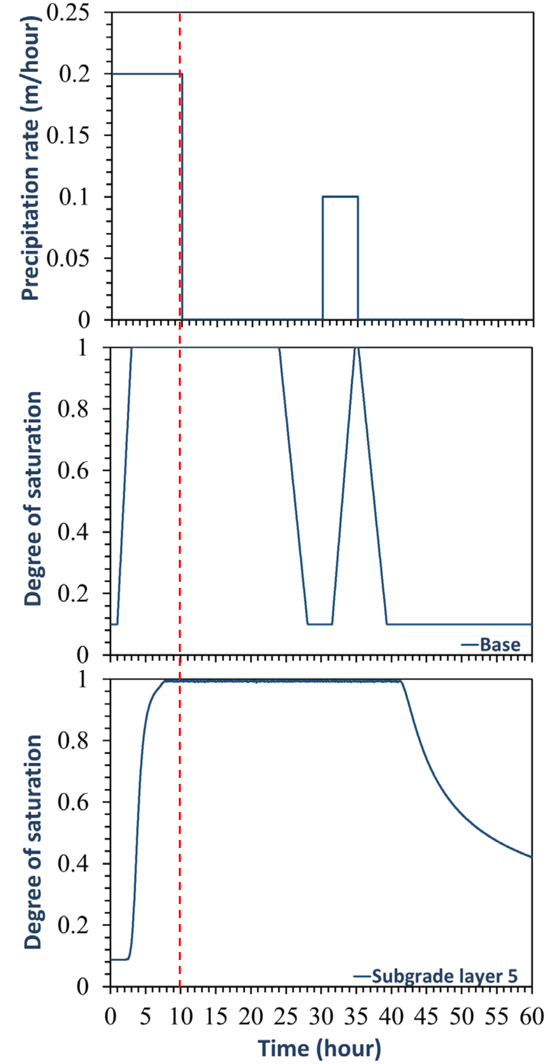




4. Hydrological Structure (6/15)

❑ Water movement simulation using the SDM

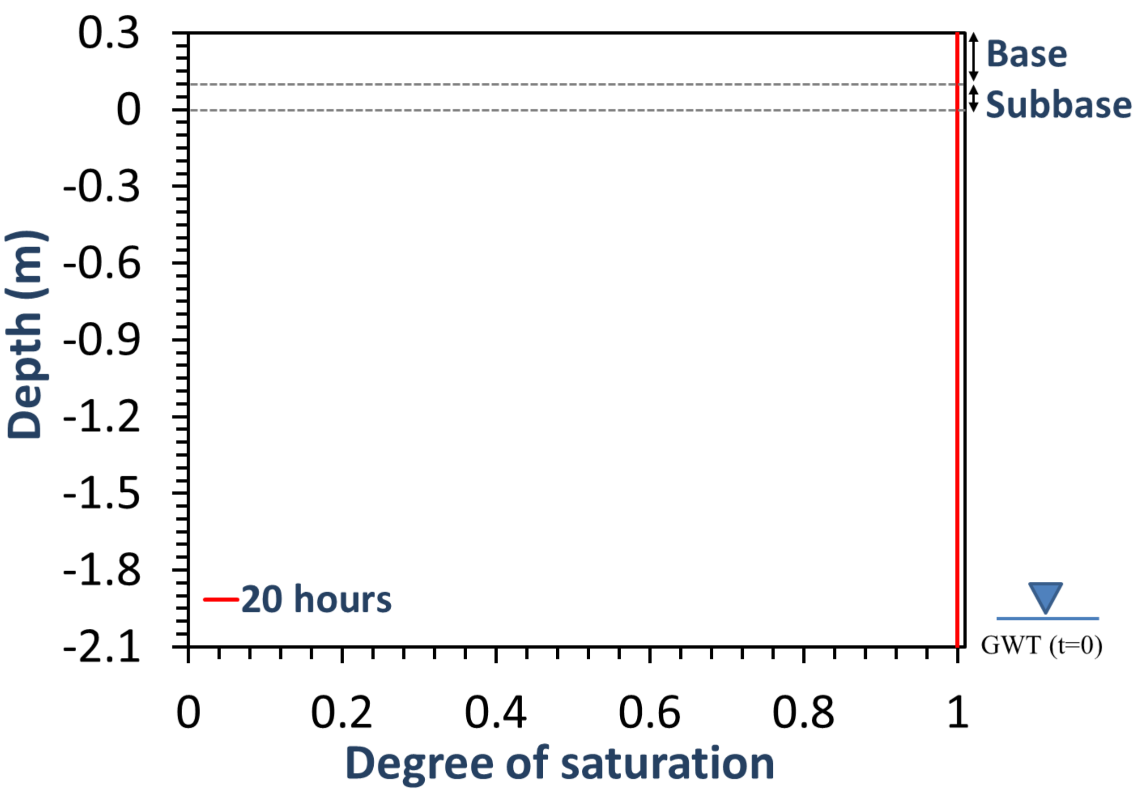


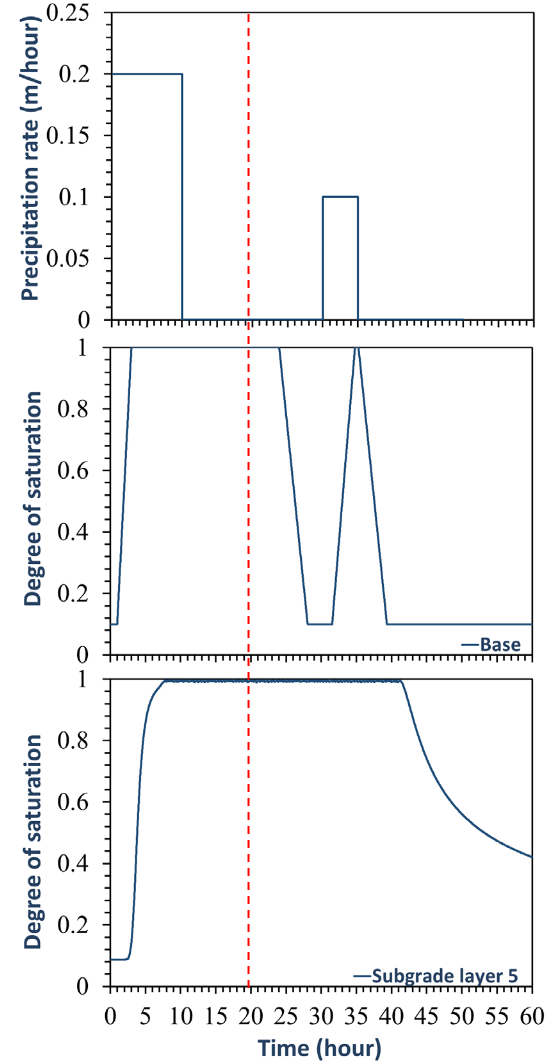


4. Hydrological Structure (7/15)

❑ Water movement simulation using the SDM

Moisture profile

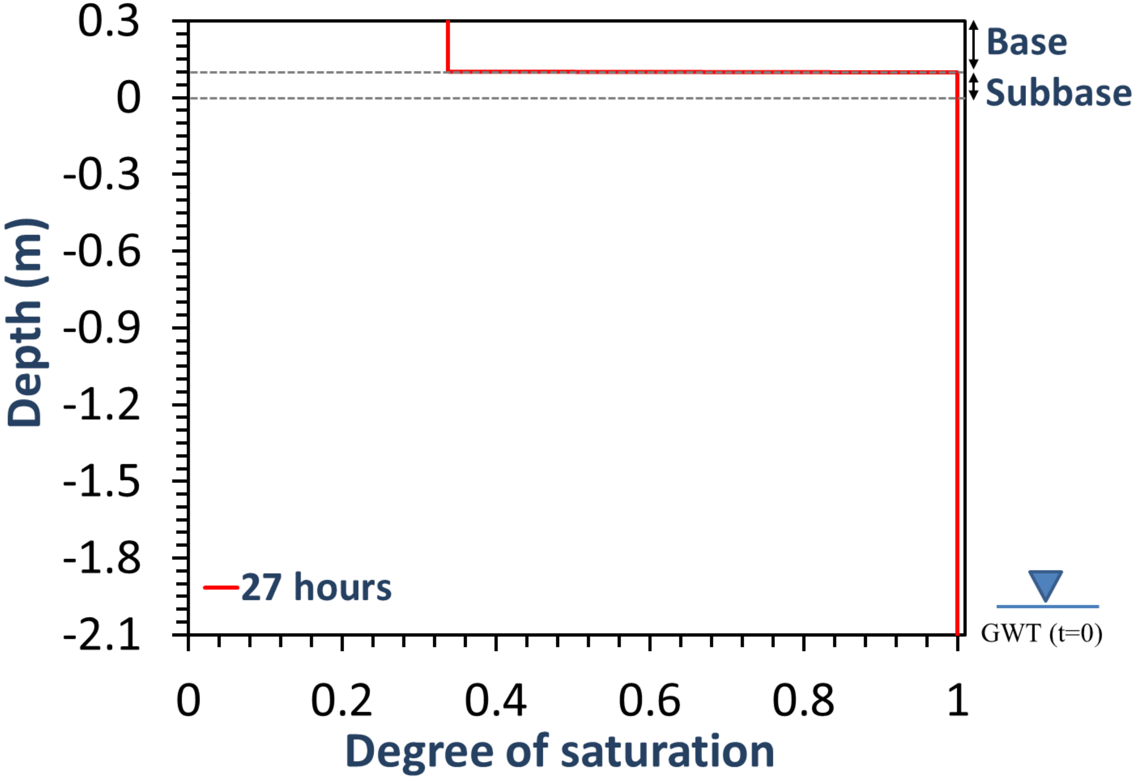


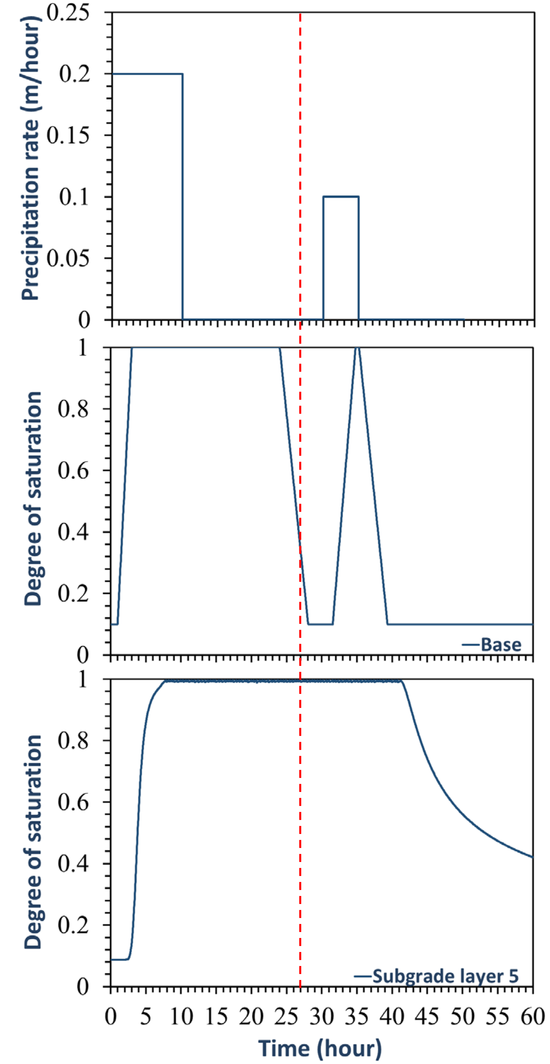


4. Hydrological Structure (8/15)

❑ Water movement simulation using the SDM

Moisture profile

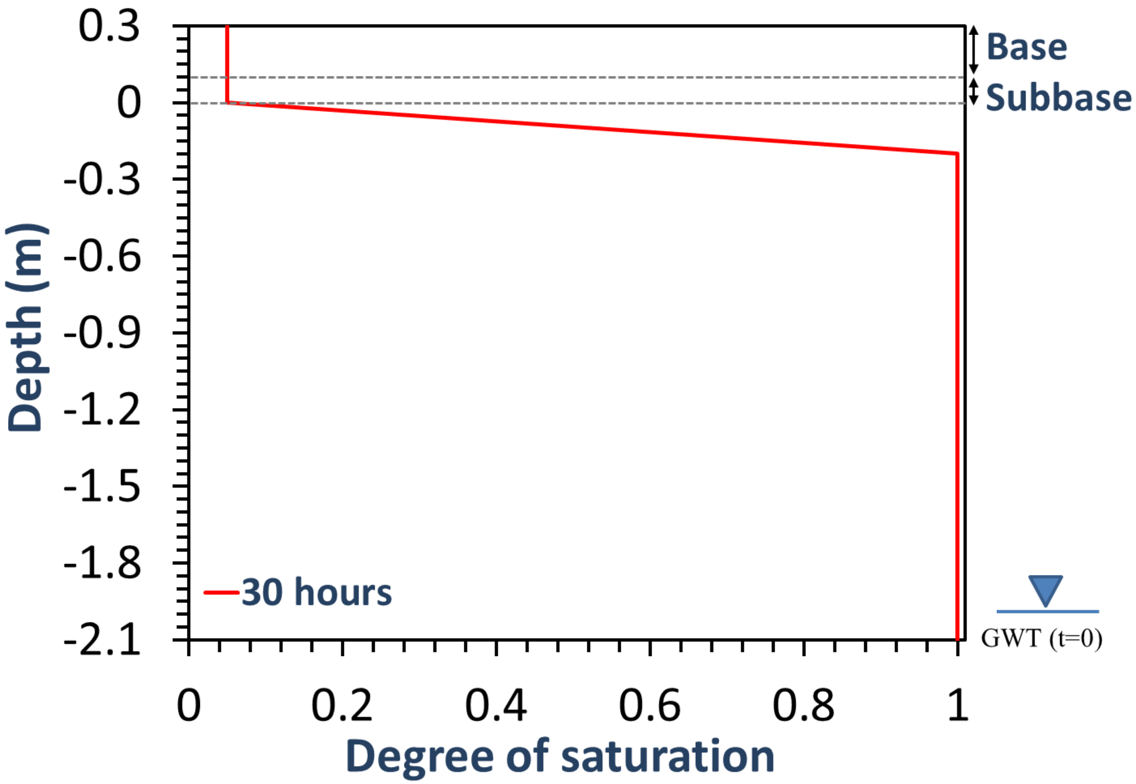


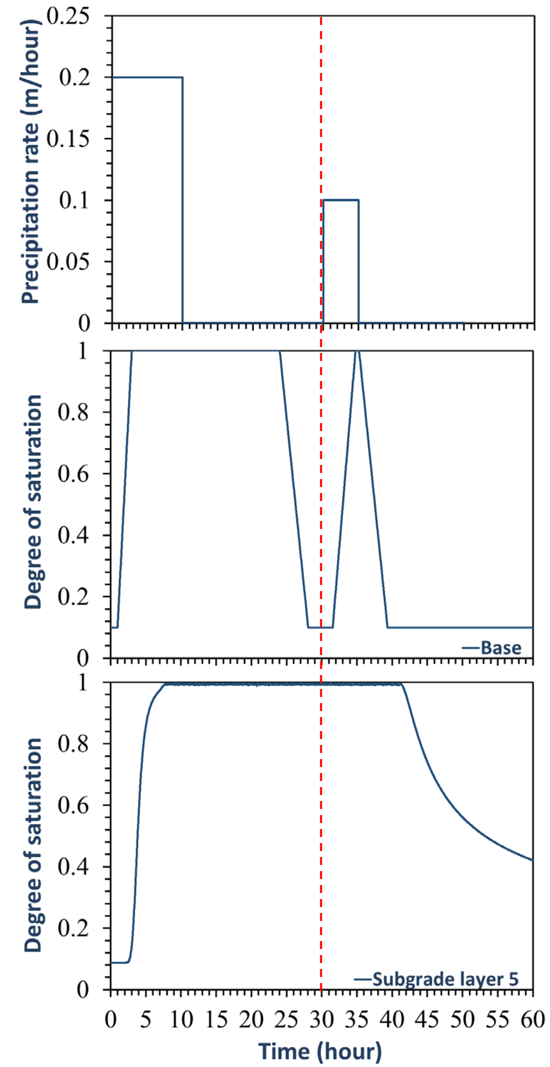


4. Hydrological Structure (9/15)

❑ Water movement simulation using the SDM

Moisture profile

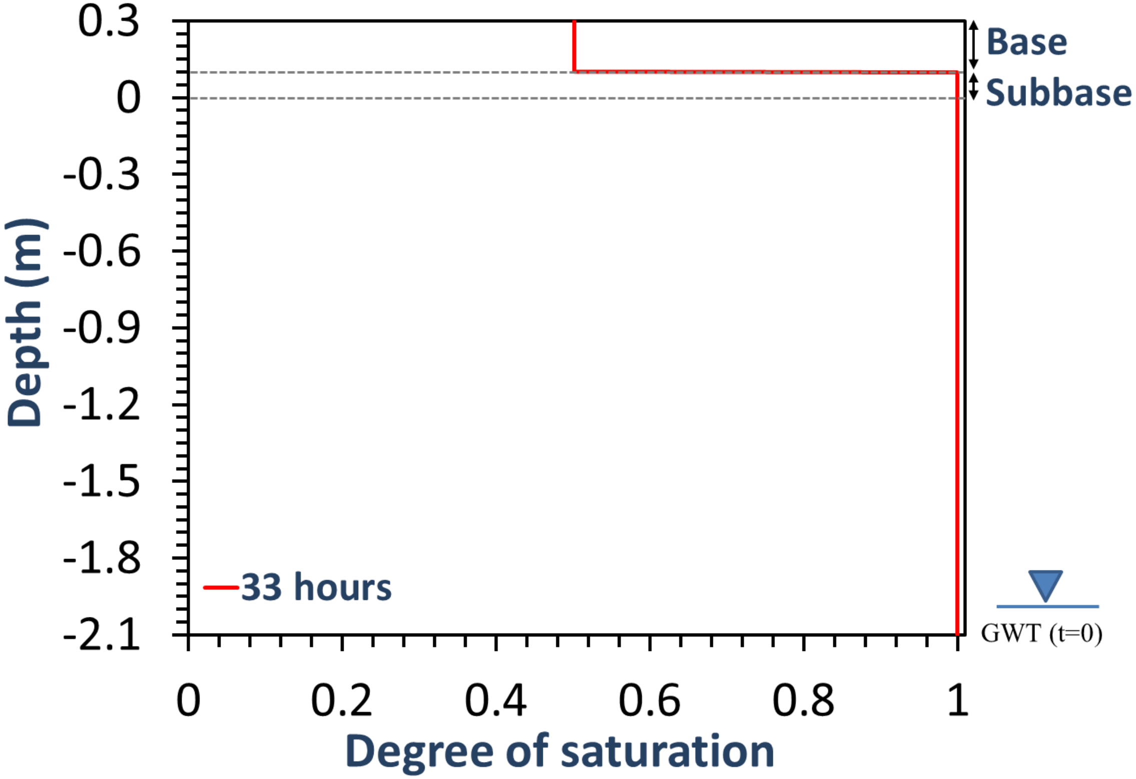


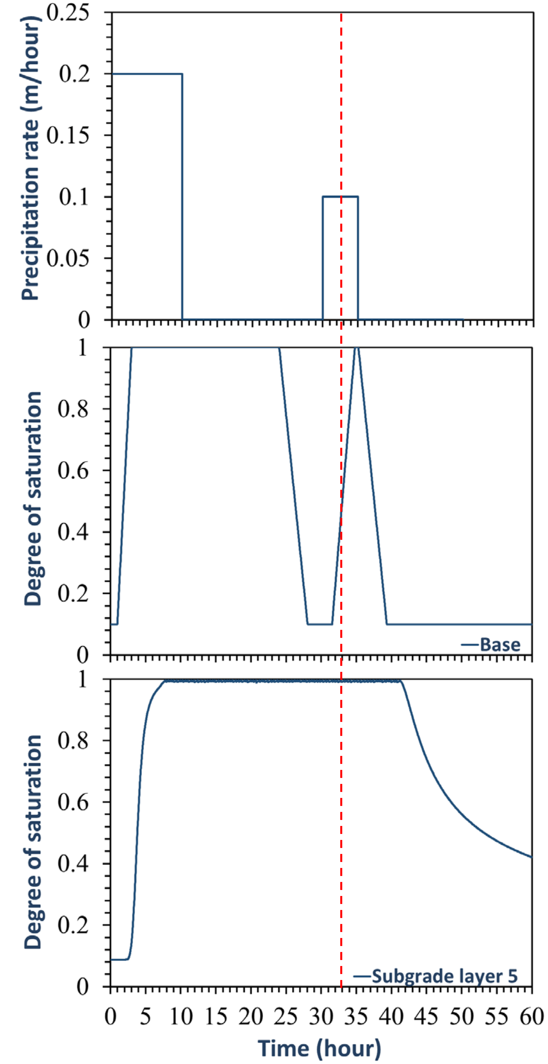


4. Hydrological Structure (10/15)

❑ Water movement simulation using the SDM

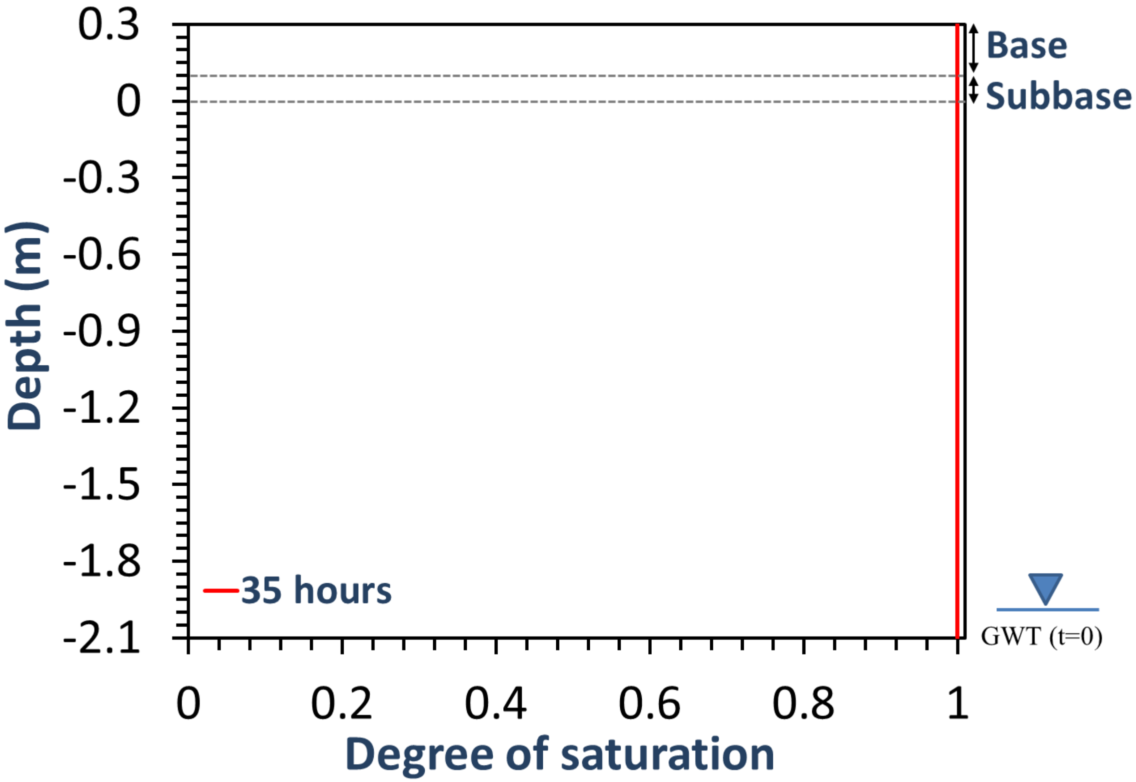
Moisture profile

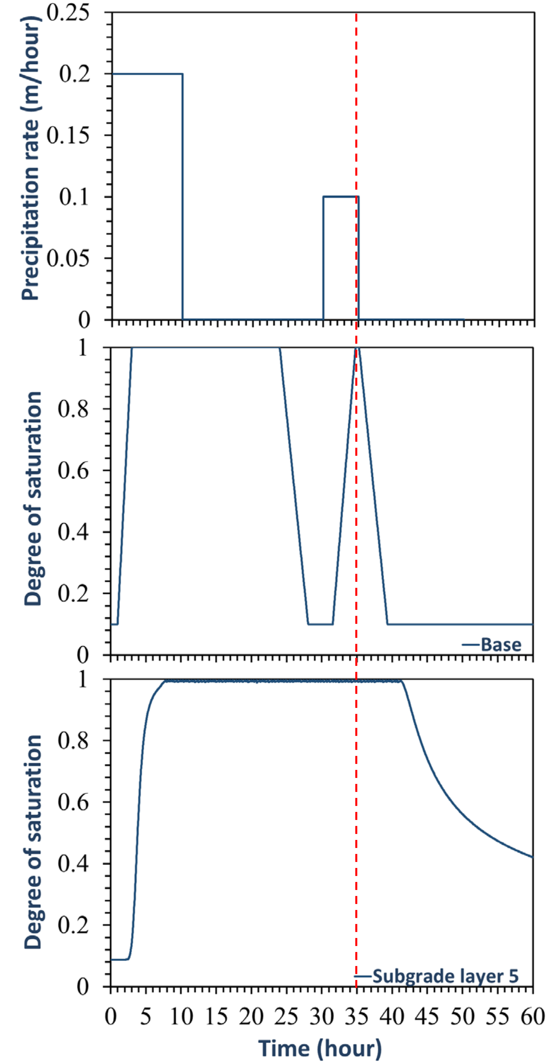




❑ Water movement simulation using the SDM

Moisture profile

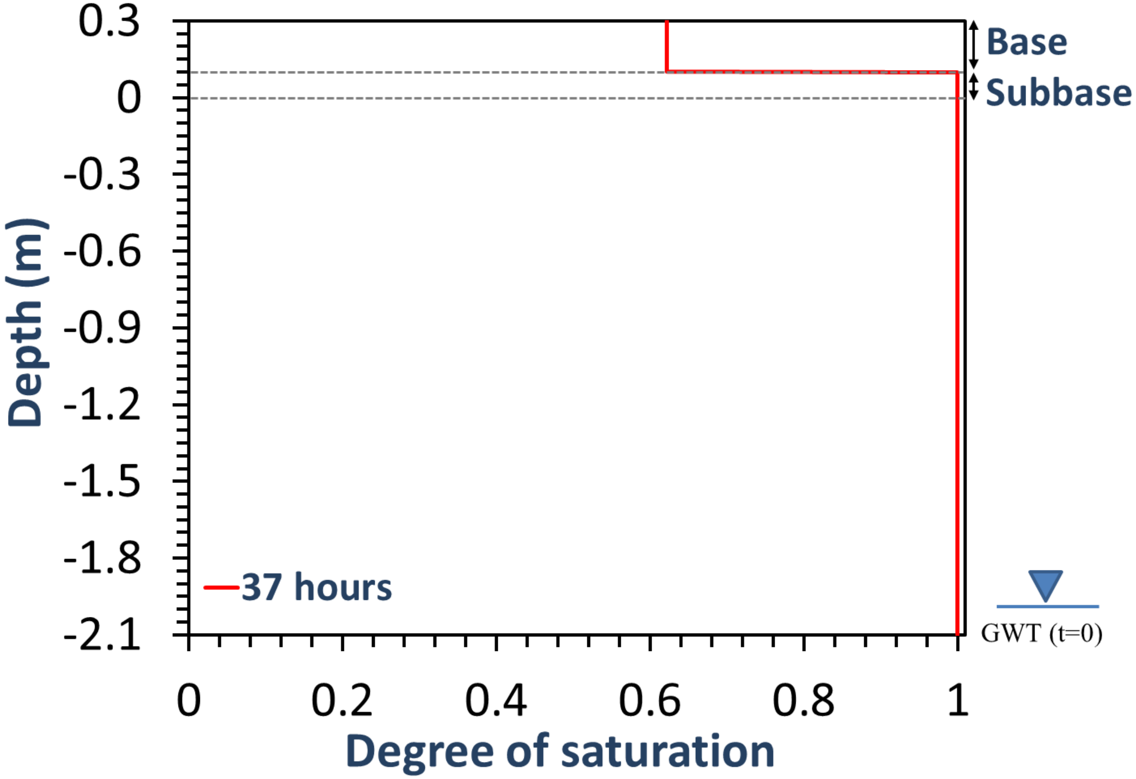


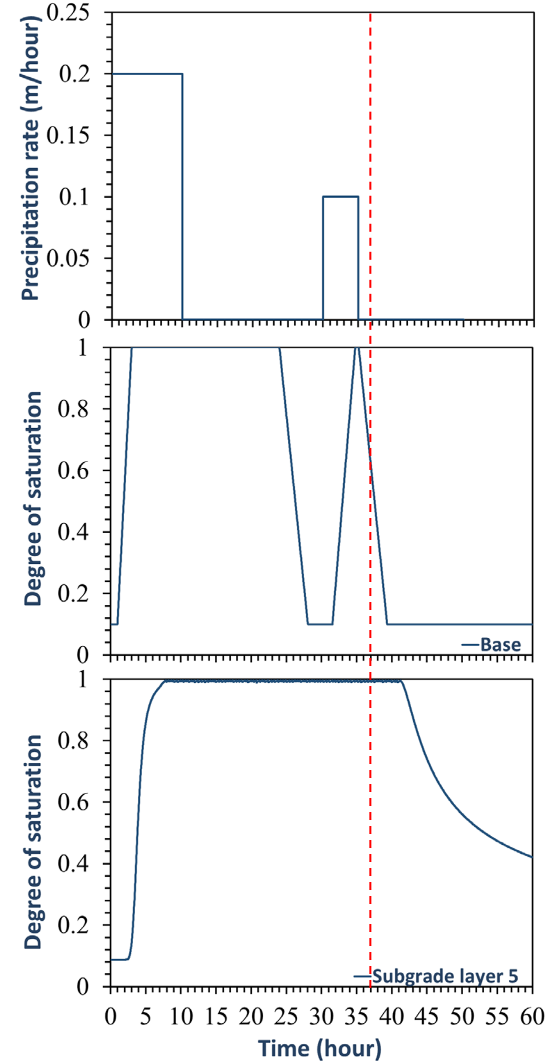


4. Hydrological Structure (12/15)

❑ Water movement simulation using the SDM

Moisture profile

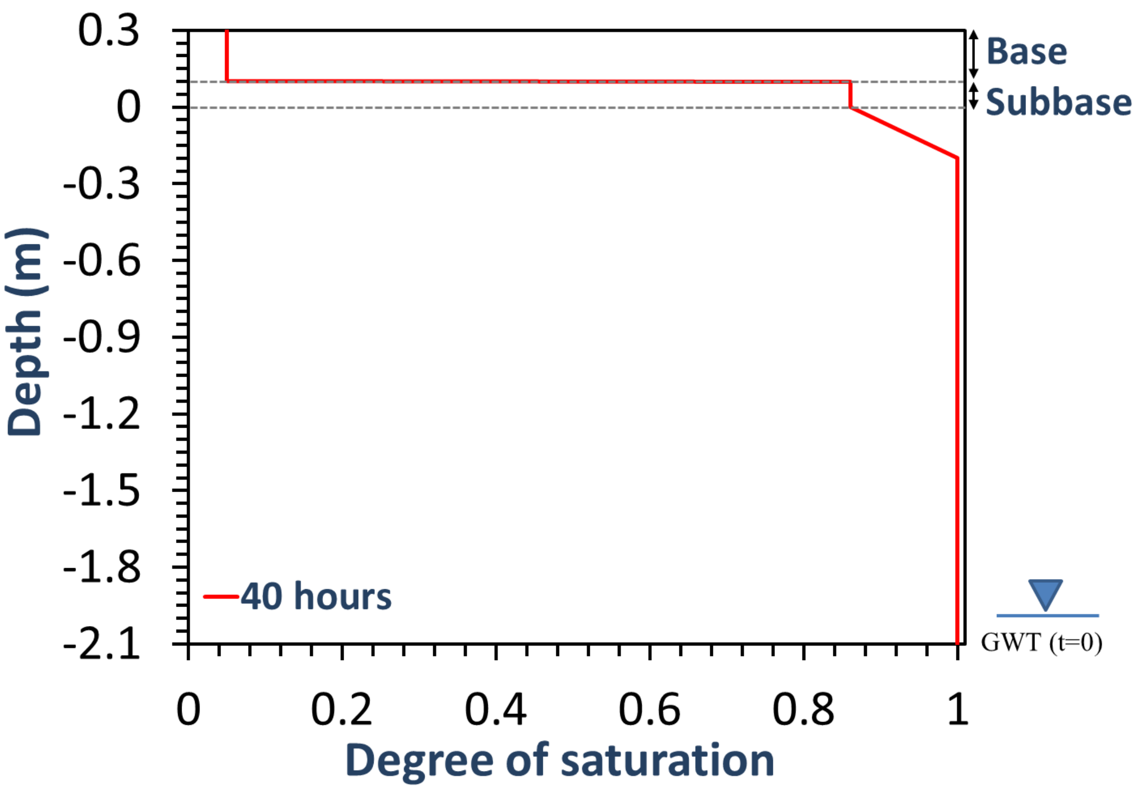


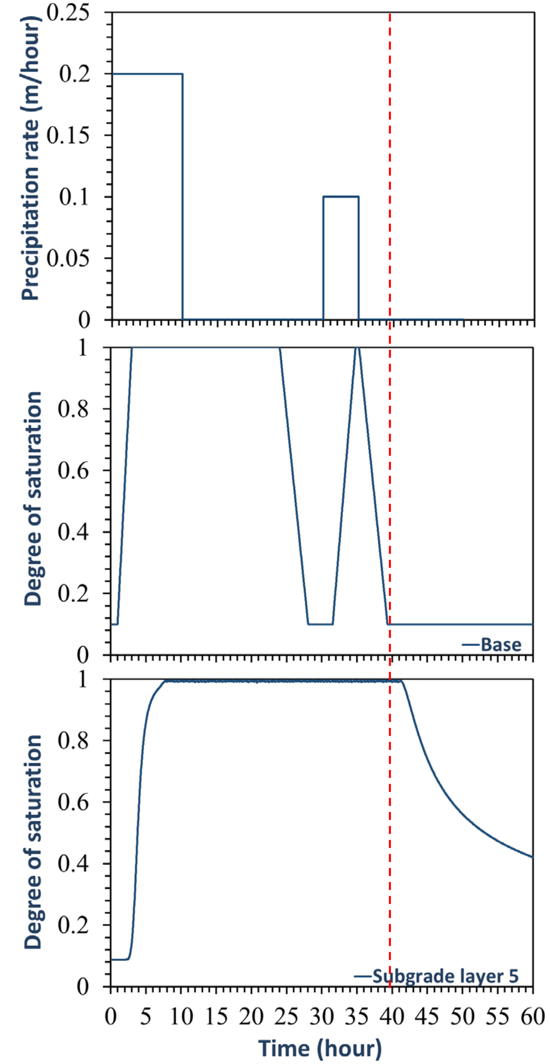


4. Hydrological Structure (13/15)

❑ Water movement simulation using the SDM

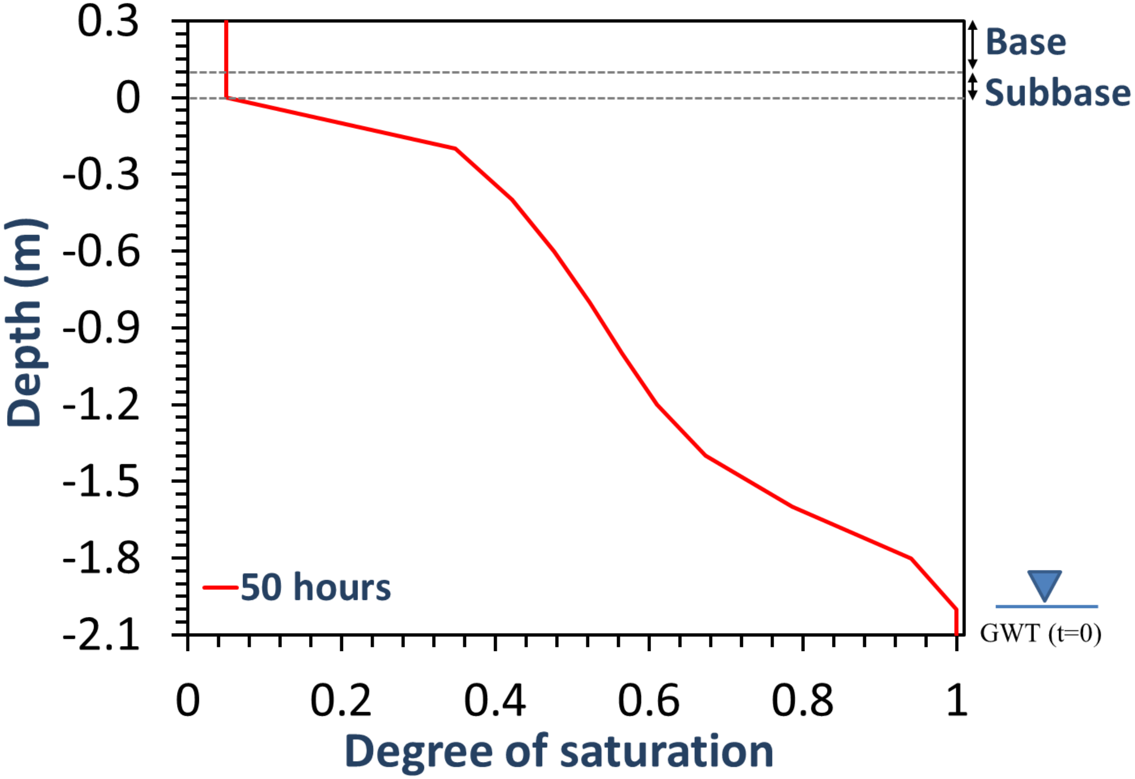
Moisture profile

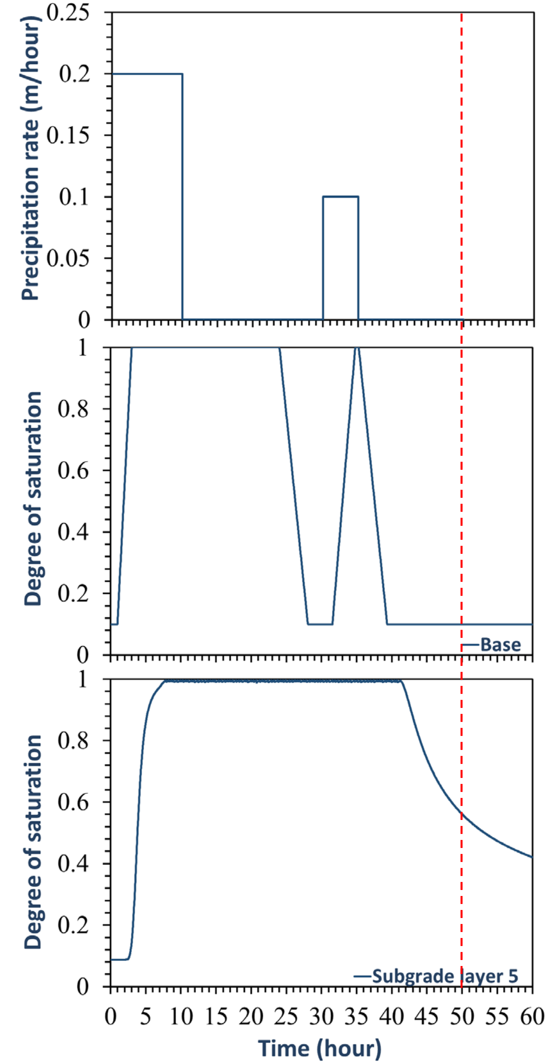




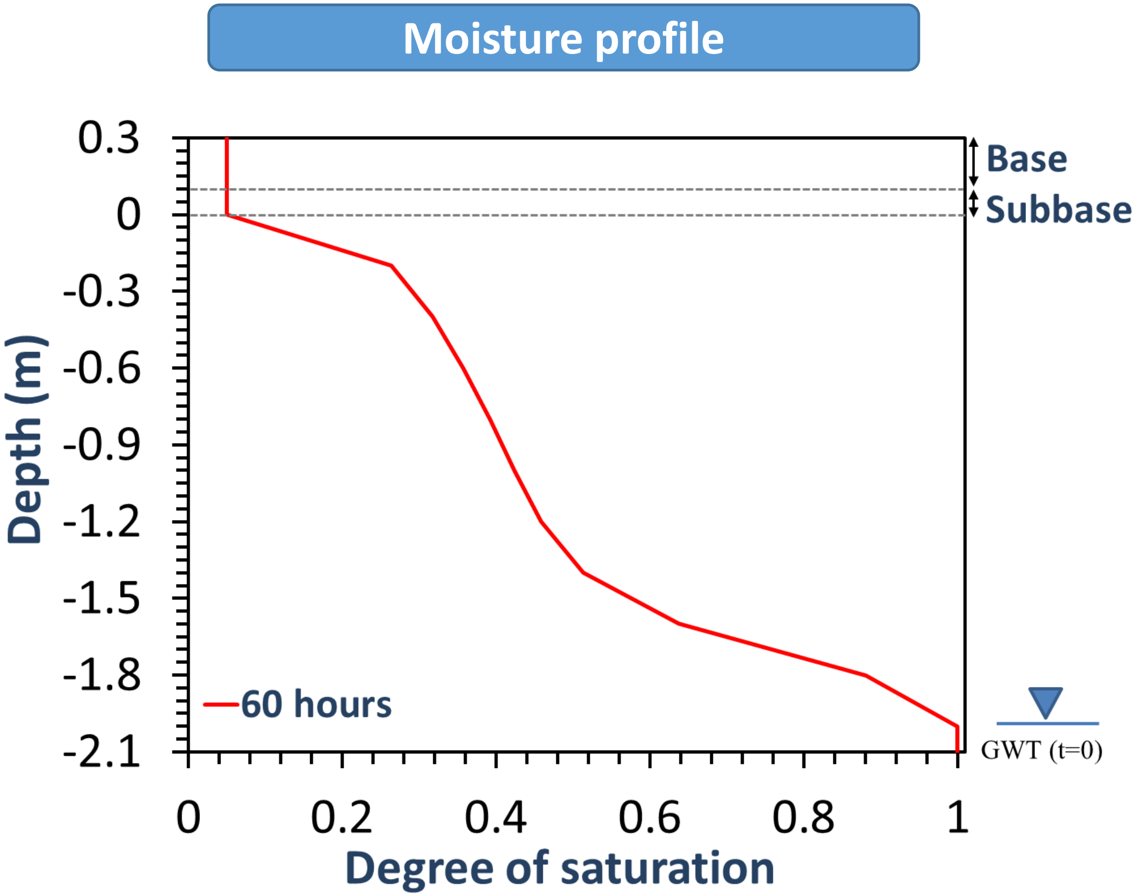
❑ Water movement simulation using the SDM

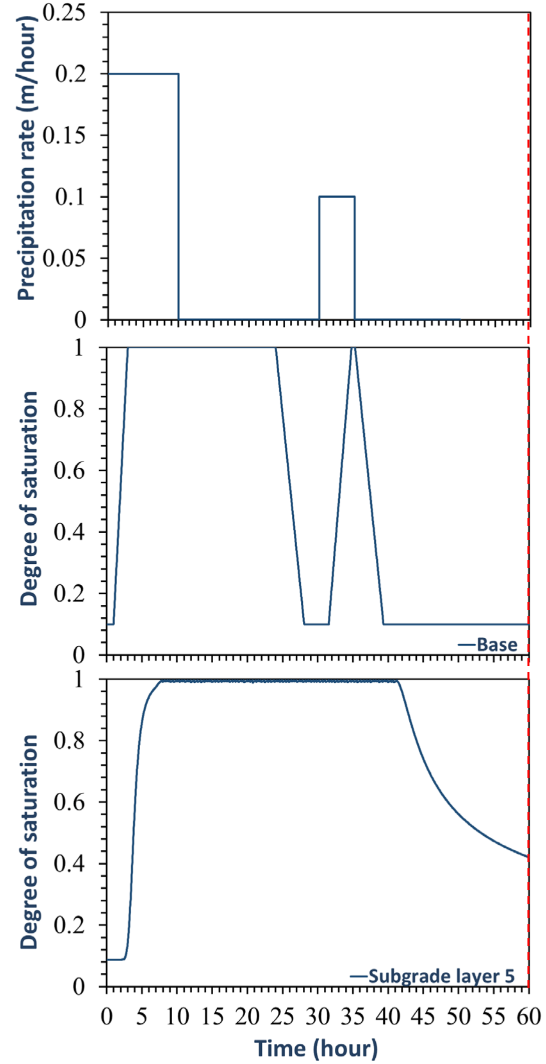
Moisture profile





❑ Water movement simulation using the SDM





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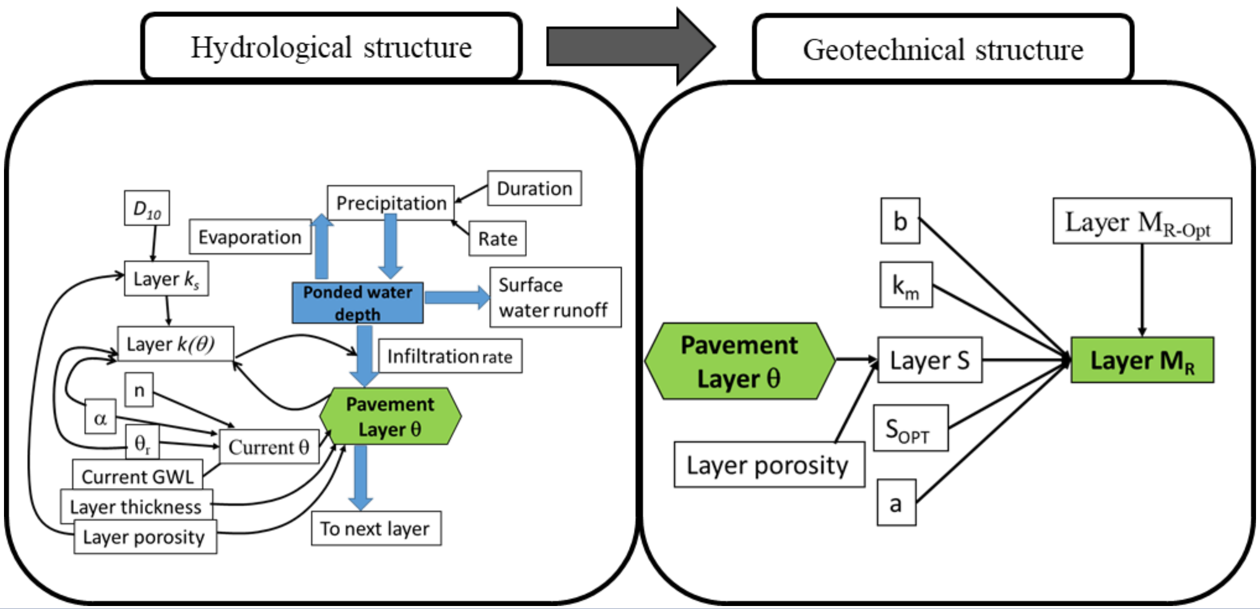
5. Geotechnical Structure (1/2)

❑ Moisture dependent resilient modulus

- Uses real time moisture profile from hydrological structure
- Estimates based on available moisture dependent resilient modulus equations
- Example: MEPDG (Zapata et al. 2007)

$$\log\left(\frac{M_R}{M_{R-OPT}}\right) = a + \frac{b-a}{1+\exp\left[\ln\left(-\frac{b}{a}\right)+k_m\left(S-S_{OPT}\right)\right]}$$



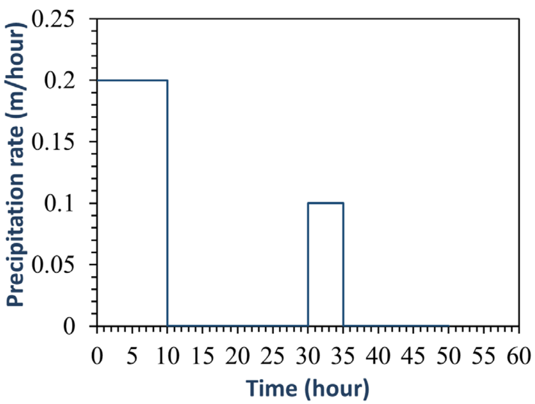
5. Geotechnical Structure (2/2)

❑ Flexible pavement example:

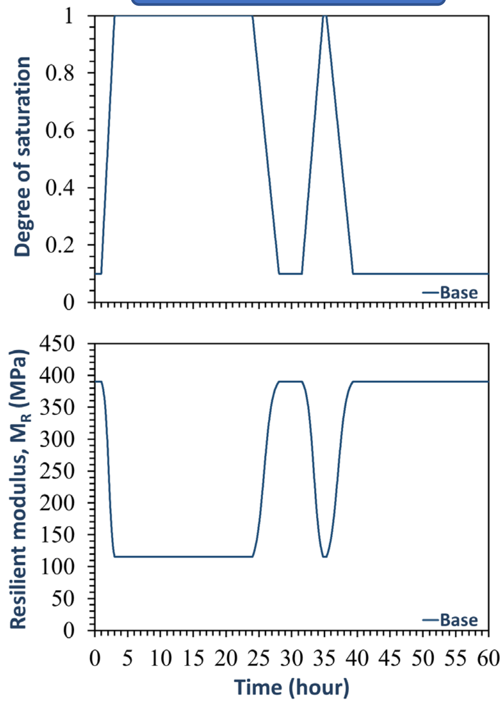
- Assumed material properties

Property/parameter (at optimum moisture content)	value
Base resilient modulus ($M_{R,B\text{-}OPT}$)	200 MPa (~30 ksi)
Subbase resilient modulus ($M_{R,SB\text{-}OPT}$)	137 MPa (~20 ksi)
Subgrade resilient modulus ($M_{R,Sg\text{-}OPT}$)	70 MPa (~10 ksi)
a	−0.3123
b	0.3
K_m	6.8157

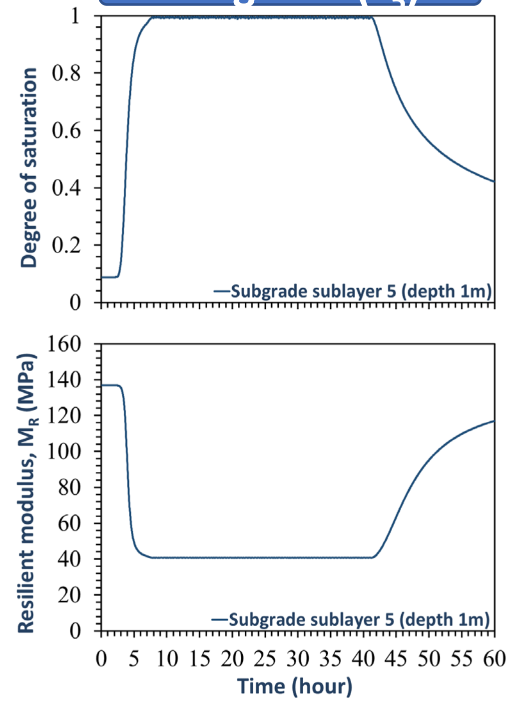
- Typical results from SDM:



Base



Subgrade (L_5)



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6. Pavement Response Structure (1/3)

❑ Main components

✓ Traffic information: axle load, axle configuration, and tire pressure

✓ Structural performance analysis:

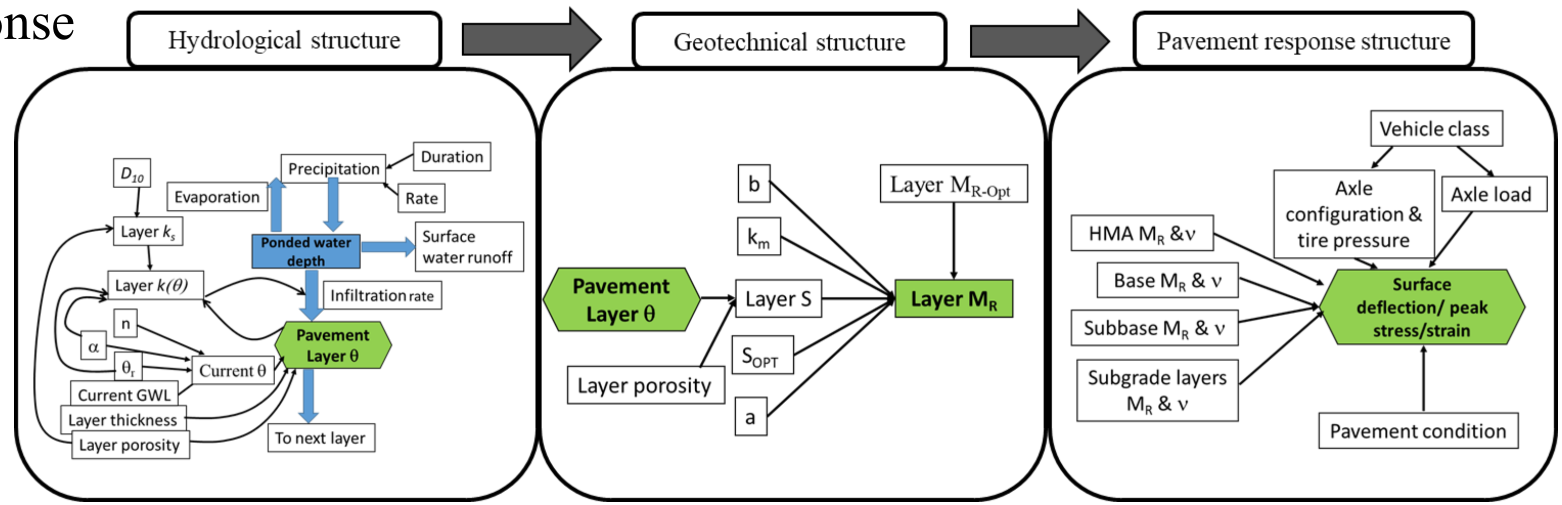
Equivalent Thickness Method (ETM)

$$H_{Eq} = H_n + \sum_{i}^{n} C_i H_i \left[\frac{E_i(1-\nu_n^2)}{E_n(1-\nu_i^2)}\right]^{1/3}$$

Linear elastic analysis

$$\sigma_z = q\left(1 - \frac{z^3}{(a^2+z^2)^{1.5}}\right)$$

- Uses M_R profile from geotechnical structure to estimate pavement response



6. Pavement Response Structure (2/3)

❑ Flexible pavement example:

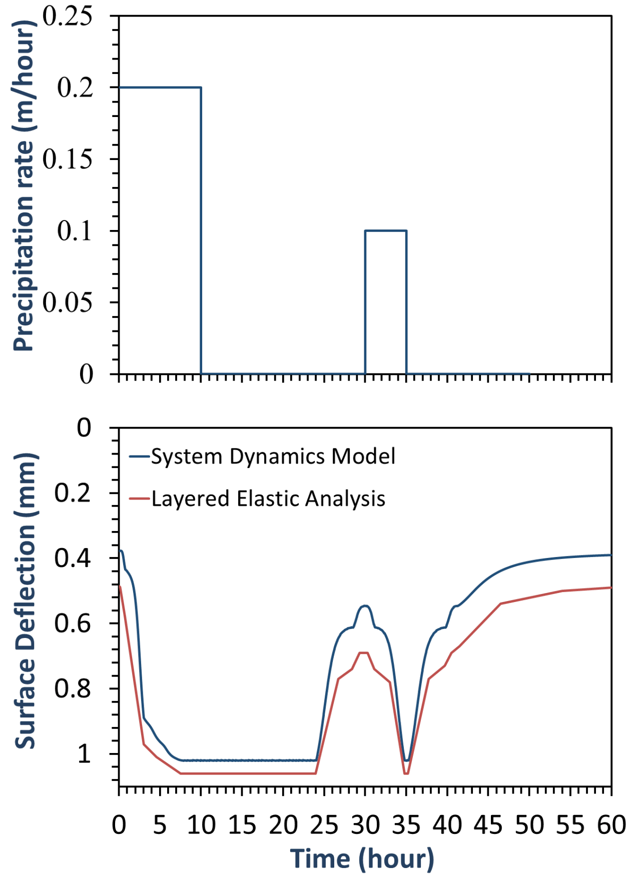
Assumed material properties

properties	value
AC resilient modulus ($M_{R,AC}$)	2500 MPa (~360 ksi)
AC Poisson ratio (ν_{AC})	0.35
Base Poisson ratio (ν_{B})	0.3
Subbase Poisson ratio (ν_{Sb})	0.3
Subgrade Poisson ratio (ν_{Sg})	0.4

Assumed traffic information

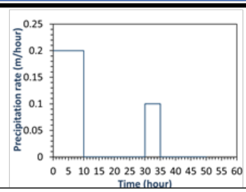
Traffic information	Value
Tire pressure	550 kPa (80 psi)
Wheel load	45 kN (10 kips)

Typical results from SDM



6. Pavement Response Structure (3/3)

Input variables



Properties	Attributes/Value
Soil type	Silty sand
Void ratio (e)	0.5
Effective grain size (D_{10})	0.035 (mm)
n_{vG}	5
α_{vG}	2
Residual volumetric water content (θ_r)	0.02
Saturated water content (θ_s)	0.3

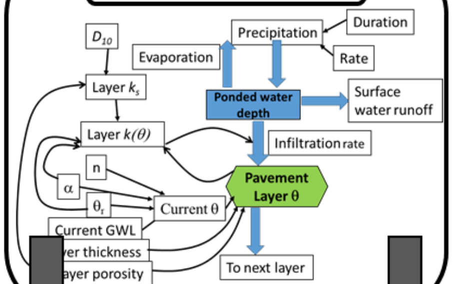
Property/parameter	value
Base optimum resilient modulus ($M_{R,B\ OPT}$)	200 MPa (~30 ksi)
Subbase optimum resilient modulus ($M_{R,SB\ OPT}$)	137 MPa (~20 ksi)
Subgrade optimum resilient modulus ($M_{R,Sg\ OPT}$)	70 MPa (~10 ksi)
a	-0.3123
b	0.3
K_m	6.8157

Traffic information	value
Tire pressure	550 kPa (80 psi)
Wheel load	45 kN (80 psi)

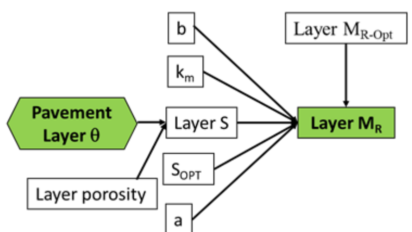
properties	value
AC resilient modulus ($M_{R,AC}$)	2500 Mpa (~360 ksi)
AC Poisson ratio (μ_{AC})	0.35
Base Poisson ratio (μ_B)	0.3
Subbase Poisson ratio (μ_{Sb})	0.3
Subgrade Poisson ratio (μ_{Sg})	0.4

SD model

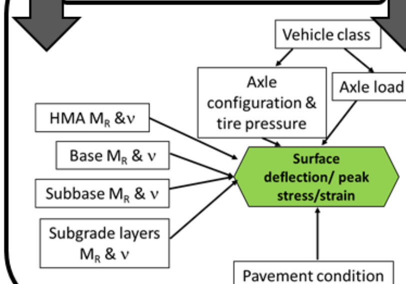
Hydrological structure



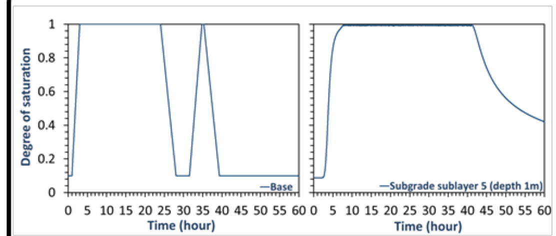
Geotechnical structure

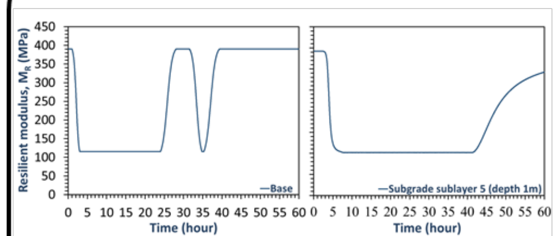


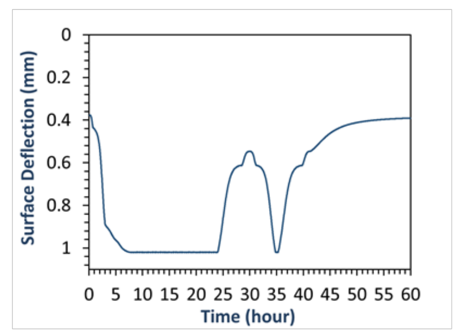
Pavement response structure



Simulation results







Outline

1. Project Overview
2. System Dynamics Model Overview
3. Hydrological Structure
4. Geotechnical Structure
5. Pavement Response Structure
6. Upcoming Tasks and Discussion

6. Upcoming Tasks and Discussion

Task1

Task2

Task3

Task4

Task5

Task6

Task7

Task8

Task9&10

Task4:
Perform full sensitivity analysis to understand the significance of stressors, pavement components, and analysis methods/formulations on overall pavement response

Task5:
develop a user-friendly toolkit that can be readily implemented for pavement load restriction decision process

Task6 and Future Phase:
Validate the toolkit using the field data/physical model testing data


Thank you!
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Durham, NH
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Saturated hydraulic conductivity

Reference	Hydraulic conductivity (cm/s)	Notation	Remarks
Hazen [11]	$k_s = cD_{10}^2$	*c*= constant.	c ≈1, applicable for fairly uniform sand
Chapius [12]	$k_s = 2.46[D_{10}^2 \frac{e^3}{(1+e)}]^{0.78}$	*e*= void ratio of soil	Applicable for uniform gravel and sand and non-plastic silty sands
Mbonimpa et al. [13]	$k_s = C_p \frac{\gamma_w}{\mu_w} \frac{e^{3+x}}{(1+e)} \frac{1}{\rho_s^2 w_L^{2\chi}}$	γ_ω=unit weight of water (kN/m3) μ_ω= Water dynamic viscosity (Pa·s) ρ_s= Density (kg/m³) of solids W_L= Liquid limit (%) x= $7.7w_L^{-0.15}$-3	Applicable for plastic soils, γ_ω ≈9.8, μ_ω ≈10^{-3}, χ=1.5