A new externally coupled physically-based multi-model framework for simulating subsurface and overland flow processes in hillslopes

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Introduction

Physically-based Watershed Models:

- Characterizing surface-subsurface
- Predicting, Planning & Designing
- Management of water resources
- Evaluating Managed aquifer recharge
- Environmental impact assessment, including climate change.

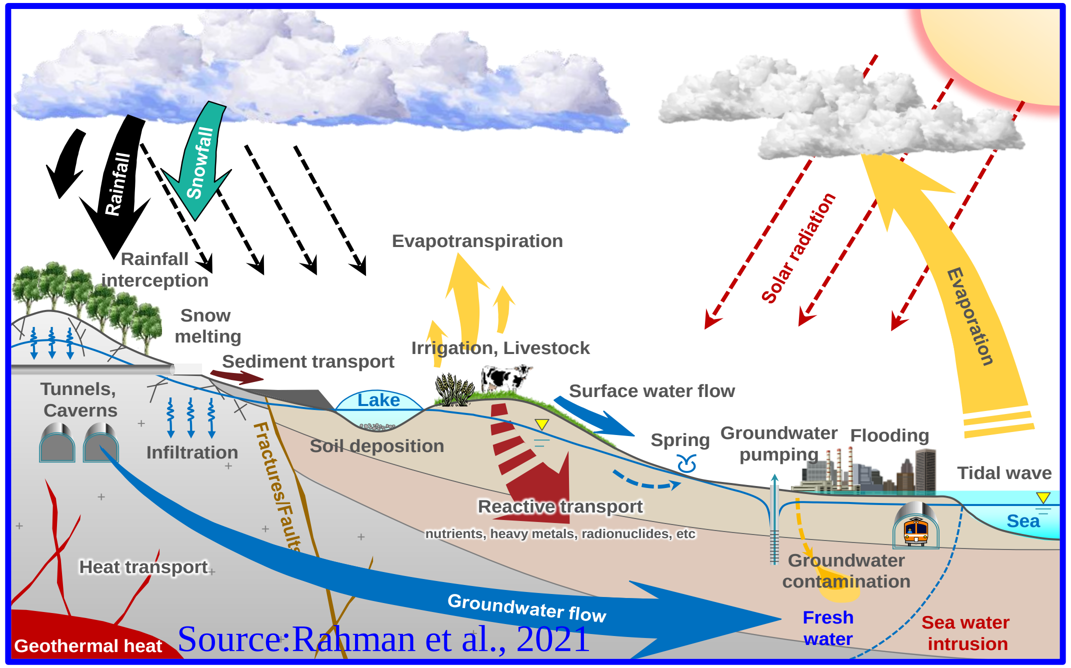
Integrated Watershed Model:

-Provides better insight into surface-subsurface interaction.

Key challenges:

- Very high computational demand
- Over parameterization
- High cost & time consuming
- High-performance computing

(Maxwell et al. 2015; Chen et al., 2022; Meles et al., 2024)



Simplified hydrological processes.

High-performance computing.

New Computationally Efficient Modeling Framework

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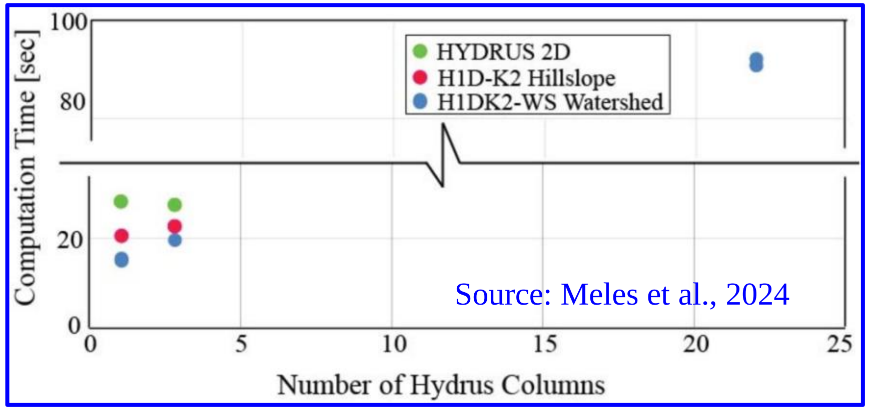
❑ Overland flow & Vadose zone:

- H1D-K2 (Chen et al., 2022; 2024)
- H1D-K2 Watershed (Meles et al, 2024)
- Computationally efficient by 47% than HYDRUS-2D
    - Dynamic time-stepping
    - Dimensionality reduction
- Parlange equation replaced by the Richard's equation.

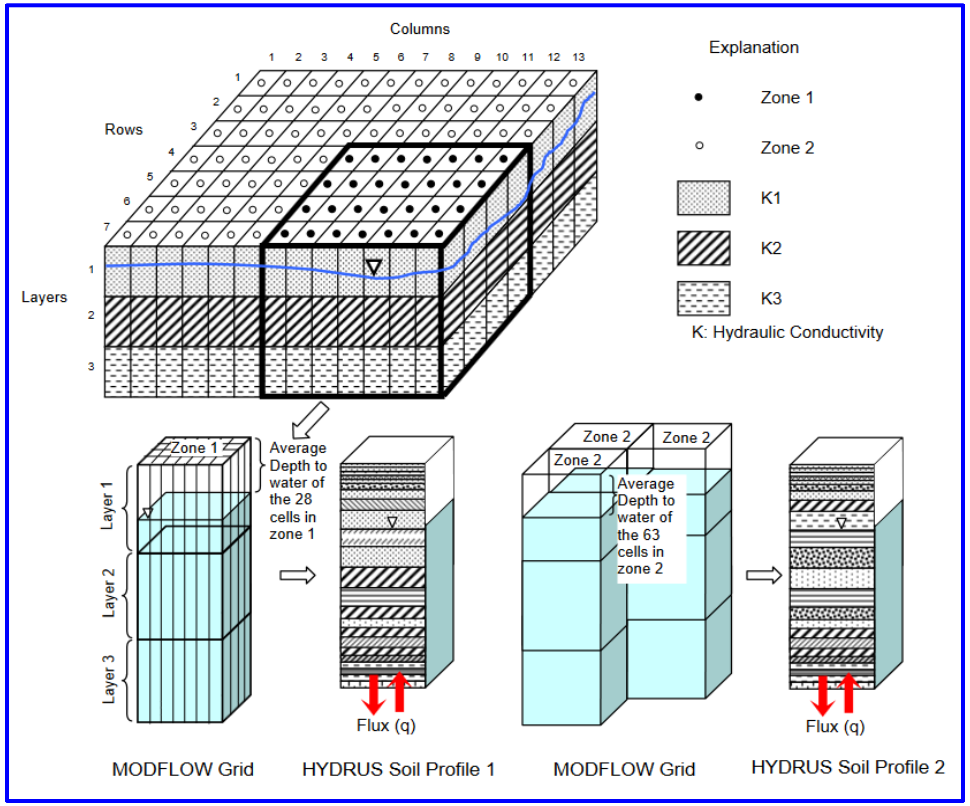
❑ Groundwater :

- **Hydrus package for MODFLOW** is an efficient model.
- First developed by Seo et al, 2007.
- Updating package (Beegum et al. 2018, 2019)
- **Python-based H1D-MF5 coupling** (Pawlowicz et al., 2024)

No attempt for coupling of H1D-K2-MF5



Computational efficiency of H1D-K2 hillslope & H1D-K2 Watershed.

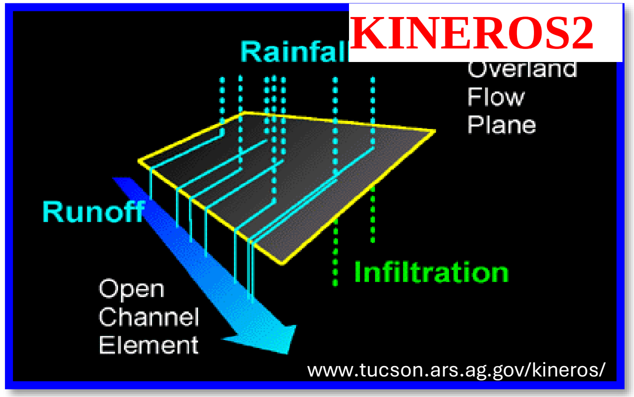


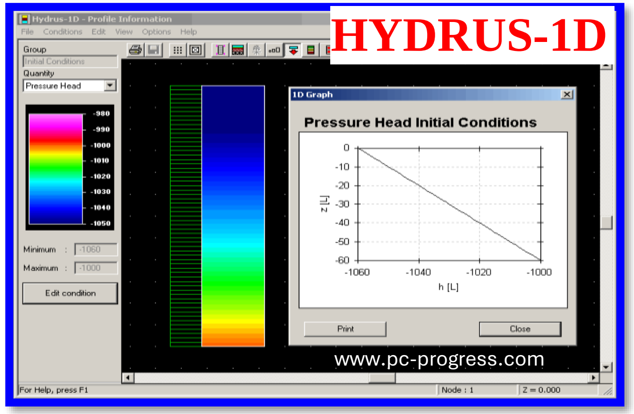
H1D package for MODFLOW (Source: Seo et al., 2007).

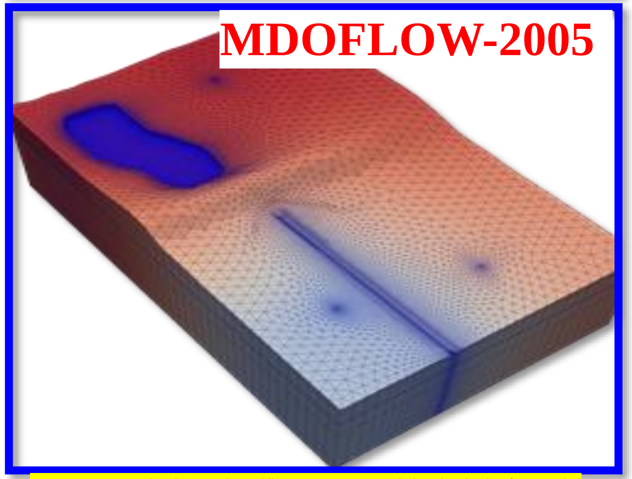
Aim & Methodology

- To develop a computationally efficient externally coupled **multi-model framework** for accurately predicting & characterizing surface-subsurface processes.

- **Python-based** multi-model framework **(H1D-K2-MF5)** is developed by external coupling of :
  - **KINEROS2:** Kinematic wave approximation of the shallow water equations for overland flow (Goodrich *et al.*, 2006).
    - A new Python script for KINEROS2
  - **HYDRUS-1D:** 1D Richards' equation for variably saturated flow (Šimůnek *et al.*, 2005).
  - **MODFLOW-2005:** 3D groundwater flow equation is derived from Darcy's Law & mass conservation principles (Harbaugh, 2005).







www.usgs.gov/software/modflow-6-usgs-modular-hydrologic-model

Externally Coupling

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Key features:

- ❑ **Switching BCs:** Surface BC in H1D is switched.
  - Atmospheric BC (no ponding)
  - Variable pressure head BC (ponding)

(Chen et al., 2022 ; Meles et al, 2024)

- ❑ **Recharge:** After each MODFLOW time step, to ensure accurate recharge estimation.
  - Pressure head is updated
  - Bottom part of the profile is modified

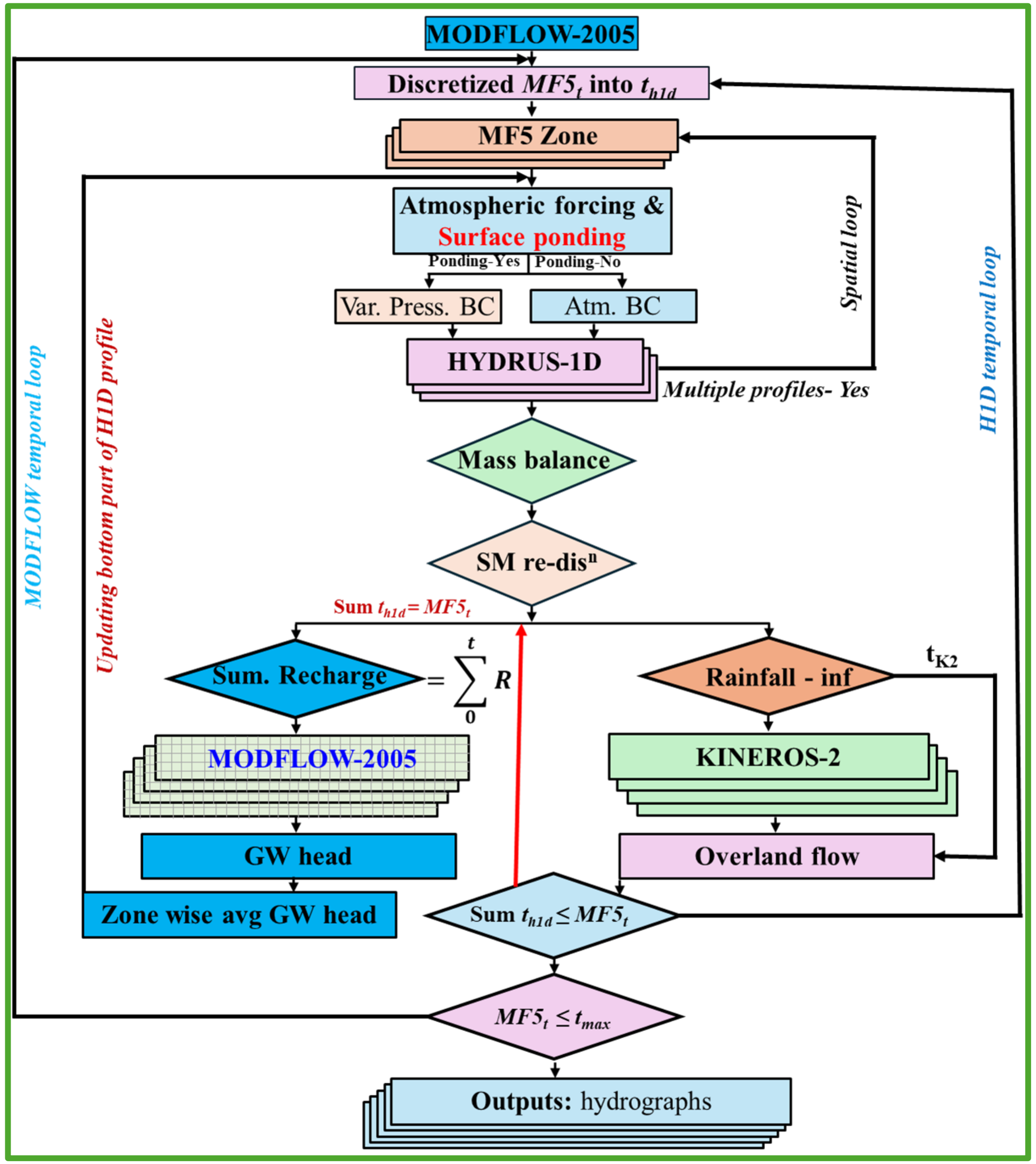
(Beegum et al., 2018; 2019)

- ❑ **Soil profile:**

  Soil profile/s is used to model a domain based on surface-subsurface conditions.

- ❑ **Water balance:**

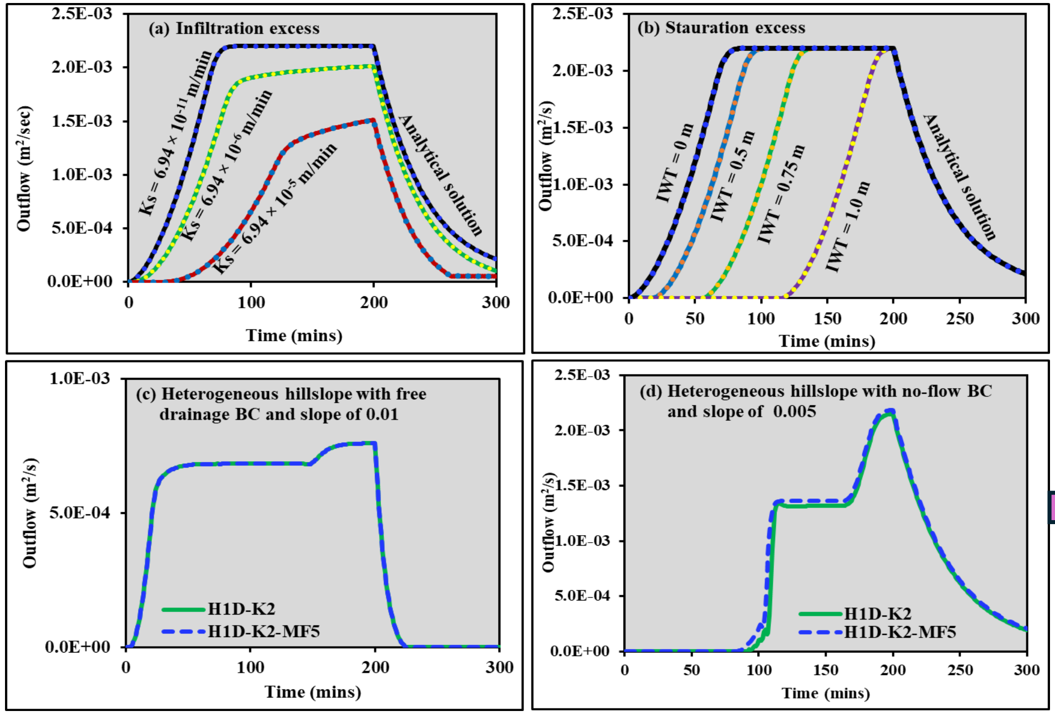
  Water balance is estimated separately for overland flow, vadose zone & groundwater.



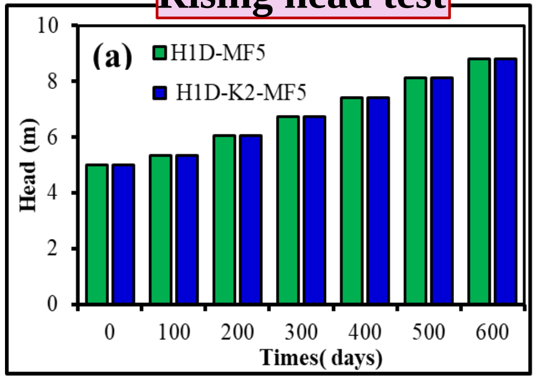
Flowchart depicting the information exchange process in H1D-K2-MF simulation code

New Python Code Verifications

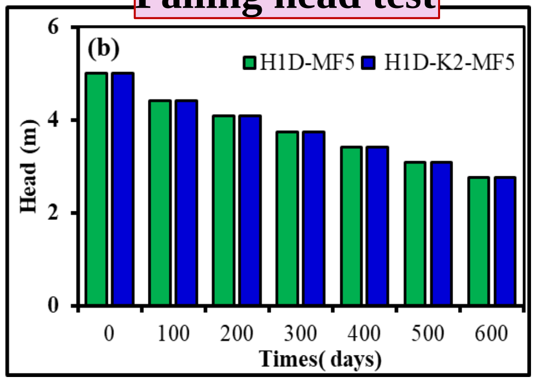
Surface & subsurface modules: Extensive verifications for overland flow, vadose zone, & groundwater flow by simulating analytical solutions & benchmark cases (Maxwell et al., 2014; Chen et al., 2022; & Beegum et al., 2018)

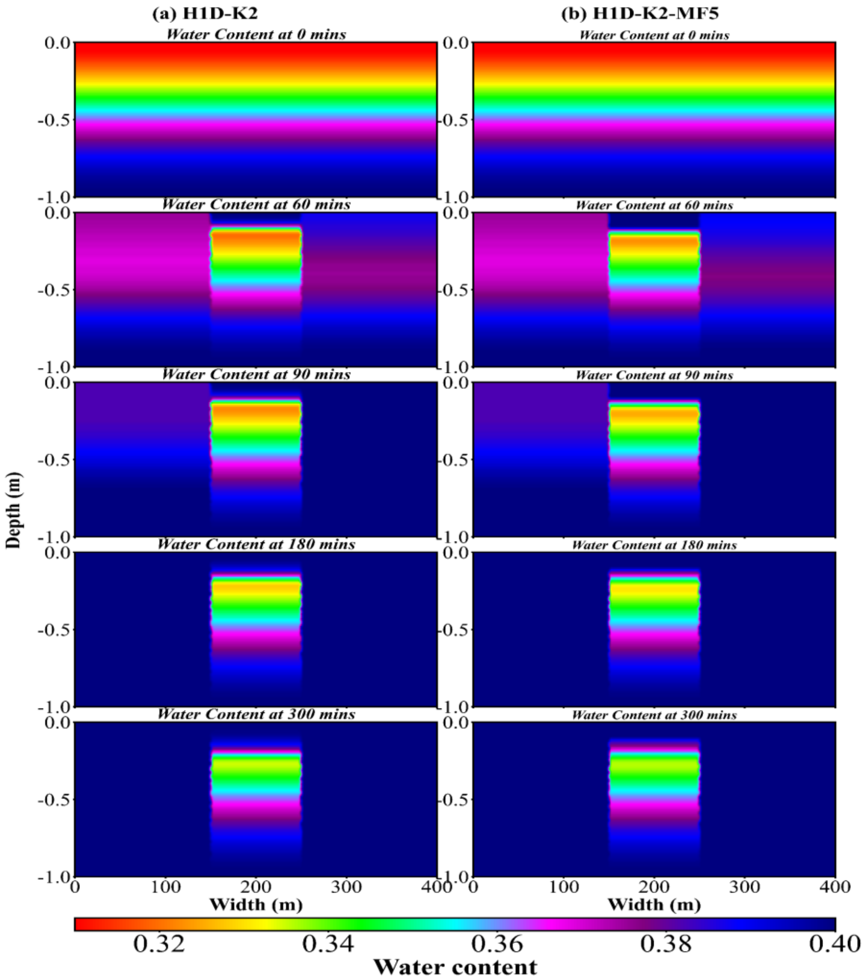


Rising head test



Falling head test





Water content distribution for heterogeneous subsurface

Results & Discussions: Homogeneous Hillslope

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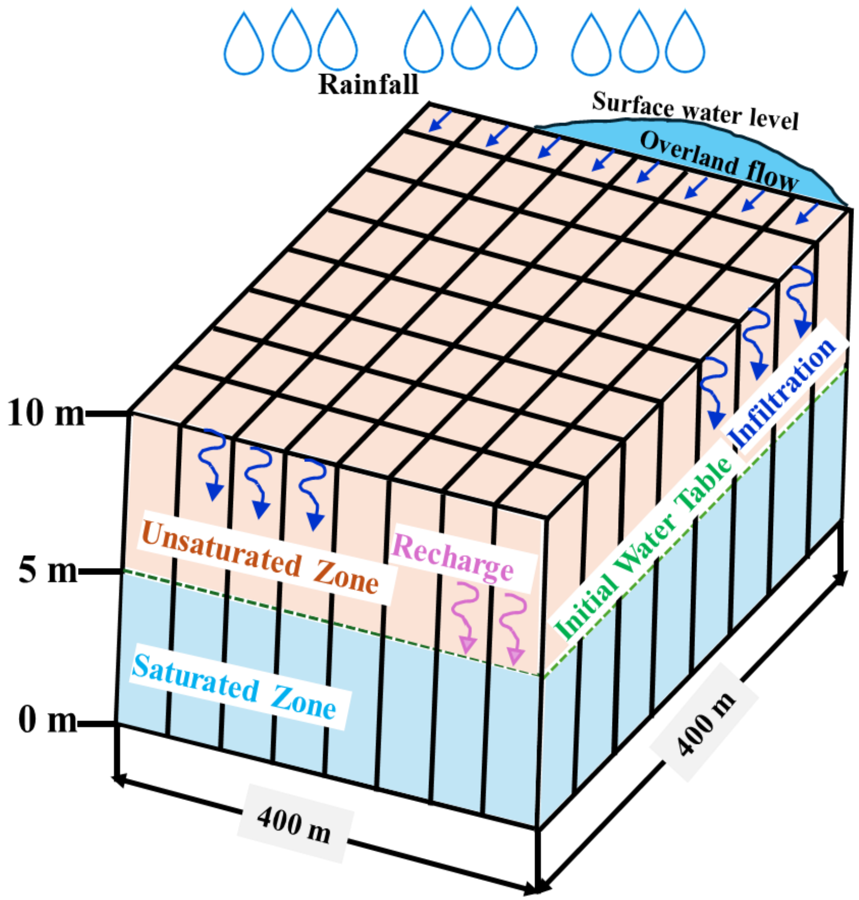

A homogeneous hillslope model domain.

❑ Hydraulic properties of material (Silt):

$\theta_r = 0.050, \theta_s = 0.489, \alpha = 0.7$ (1/m),
$n = 1.68, k_s = 7.64E-4(\frac{m}{min}), l = 0.5$

❑ Model:

- MODFLOW
  - ❖ Domain = 400 m × 400 m
  - ❖ Discretization = 8 × 8
  - ❖ Initial head = 5 m
  - ❖ Model thickness = 10 m
- H1D profile depth = 10 m
- K2 Slope = 0.005

❑ Simulation Exchange time:

- H1D- 2 min
- K2 – 1 min
- MF5- 1 day

- Simulation period: 5 days
- Precipitation rate: 1.65 E-3 (m/min)
- Precipitation duration: 200 min/day

Results & Discussions: Homogeneous Hillslope

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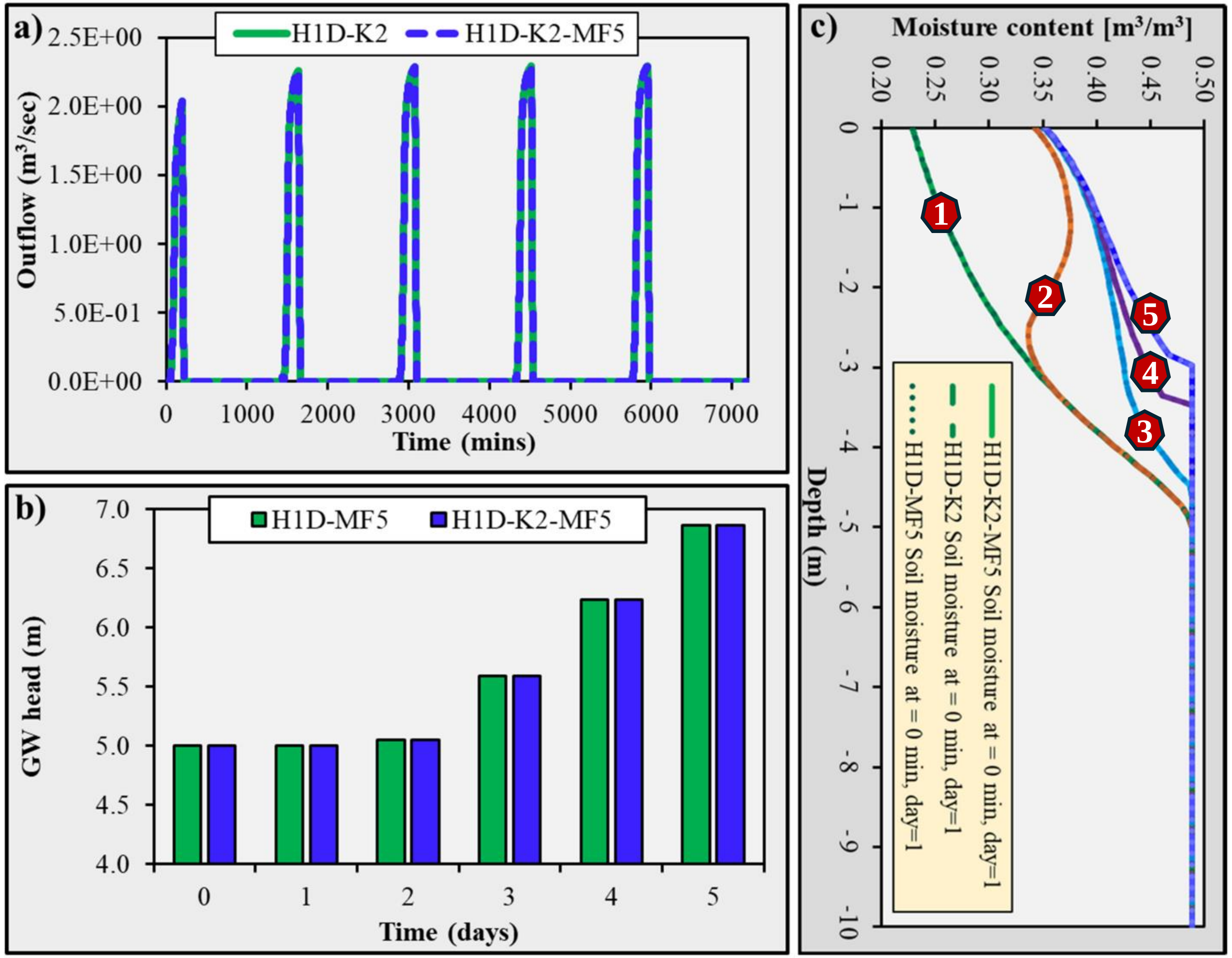
Simulation Comparisons:

- **Overland flow**
  Excellent agreement between H1D-K2 & new coupled model.
- **Groundwater**
  Groundwater head also shows almost identical agreement between H1D-MF5 & new model.
- **Water content**
  Temporal moisture dynamics of the three models show almost perfect agreement.



Comparison of H1D-K2-MF5 outputs with H1D-K2 & H1D-MF5 models for homogeneous hillslope a) the overland flow hydrograph, b) the groundwater head, c) water content dynamics over the simulation period.

Results & Discussions: Homogeneous Hillslope

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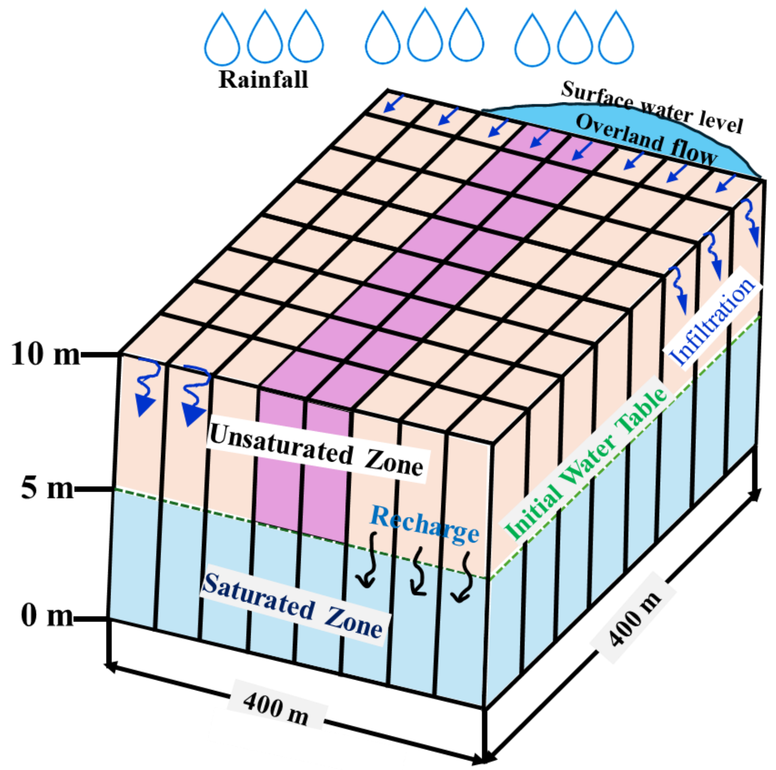
Water balance component comparisons for homogeneous hillslope

Surface and Vadose Zone						Groundwater				
Q in (m^3)	Q out (m^3)	Q storg surf (m^3)	Q storg sub change (m^3)	Q drain (m^3)	Discrepancy (%)	Recharge In (m^3)	Total In (m^3)	Storage Out (m^3)	Total Out (m^3)	Discrepancy (%)
H1D-K2 model						**H1D-MF5**				
264000.00	91161.39	0.00	95928.22	86385.44	3.53	86385.44	86385.47	86385.47	86385.47	2.95E-05
H1D-K2-MF5 Model										
264000.00	91161.39	0.00	95928.22	86385.44	3.53	86385.44	86385.47	86385.47	86385.47	2.95E-05

- ❑ An Excellent agreement between H1D-K2 and H1D-K2-MF5 for surface & vadose zone
- ❑ Almost identical agreement between H1D-MF5 & H1D-K2-MF5 for groundwater

Results & Discussions: Heterogenous Hillslope



A heterogeneous hillslope model domain.

❑ Hydraulic properties of materials (Silt):

Mat 1: $\theta_r = 0.050$, $\theta_s = 0.489$, $\alpha = 0.45$ (1/m), $n = 1.68$, $k_s = 2 * 3.82\mathrm{E}-4(\frac{\mathrm{m}}{min})$, $l = 0.5$

Mat 2: $\theta_r = 0.050$, $\theta_s = 0.489$, $\alpha = 0.45$ (1/m), $n = 1.68$, $k_s = 3 * 3.82\mathrm{E}-4(\frac{\mathrm{m}}{min})$, $l = 0.5$

❑ Model:

Same setup as the homogeneous case

- ❖ Simulation period: 5 days
- ❖ Precipitation rate: 1.65 E-3 (m/min)
- ❖ Precipitation duration: 200 min/day

❑ Simulation Exchange time:

- H1D - 10 min
- K2 - 1 min
- MF5 -1 day

Results & Discussions: Heterogenous Hillslope

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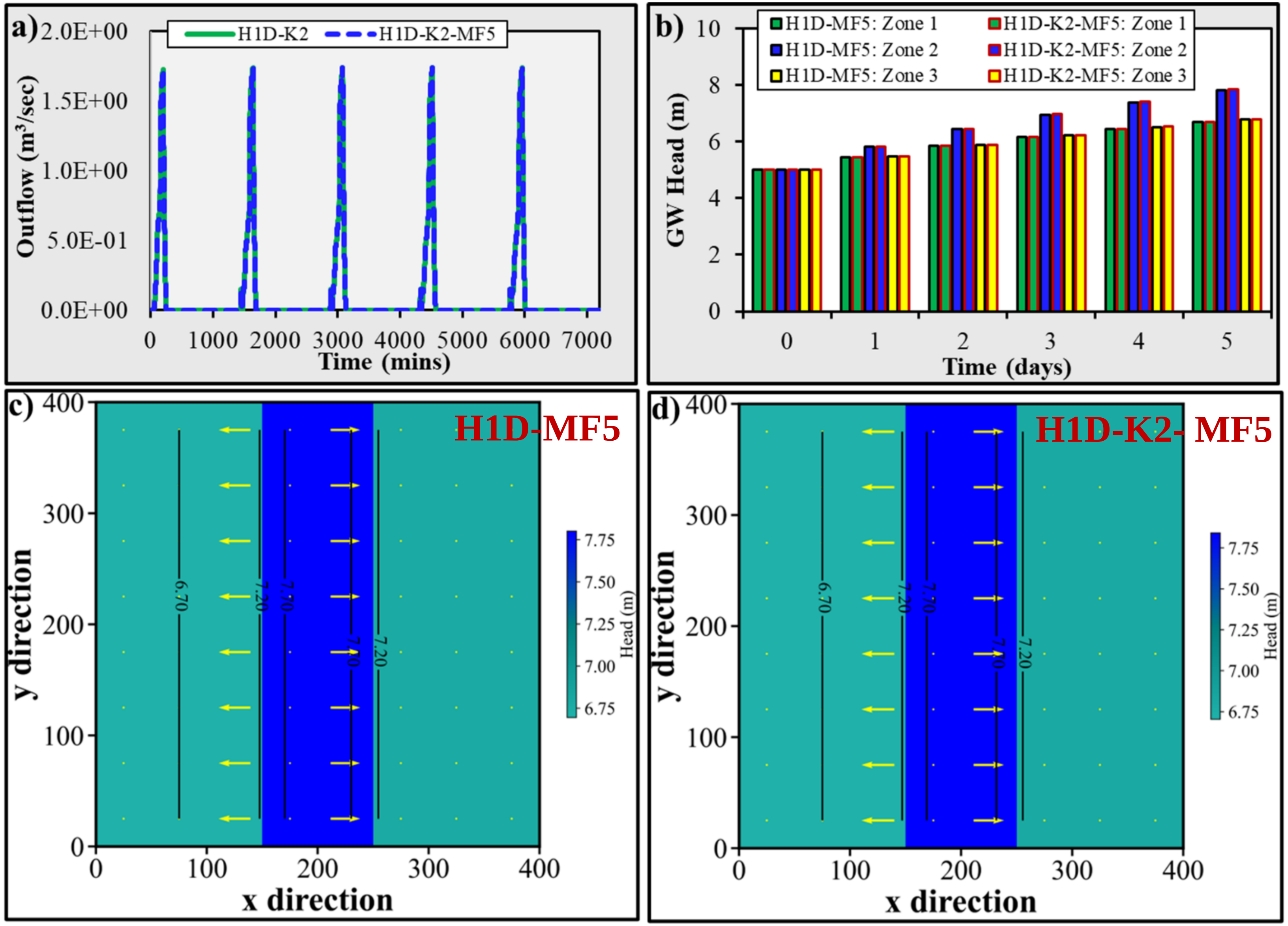

Comparing new coupled model outputs with H1D-K2 and H1D-MF5 models for heterogenous hillslope.

Overland flow:

H1D-K2 & H1D-K2-MF5 show almost identical agreement.

Groundwater:

Zone-wise temporal & spatial distribution of GW head show similar patterns.

Results & Discussions: Heterogenous Hillslope

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Comparisons of water content distributions

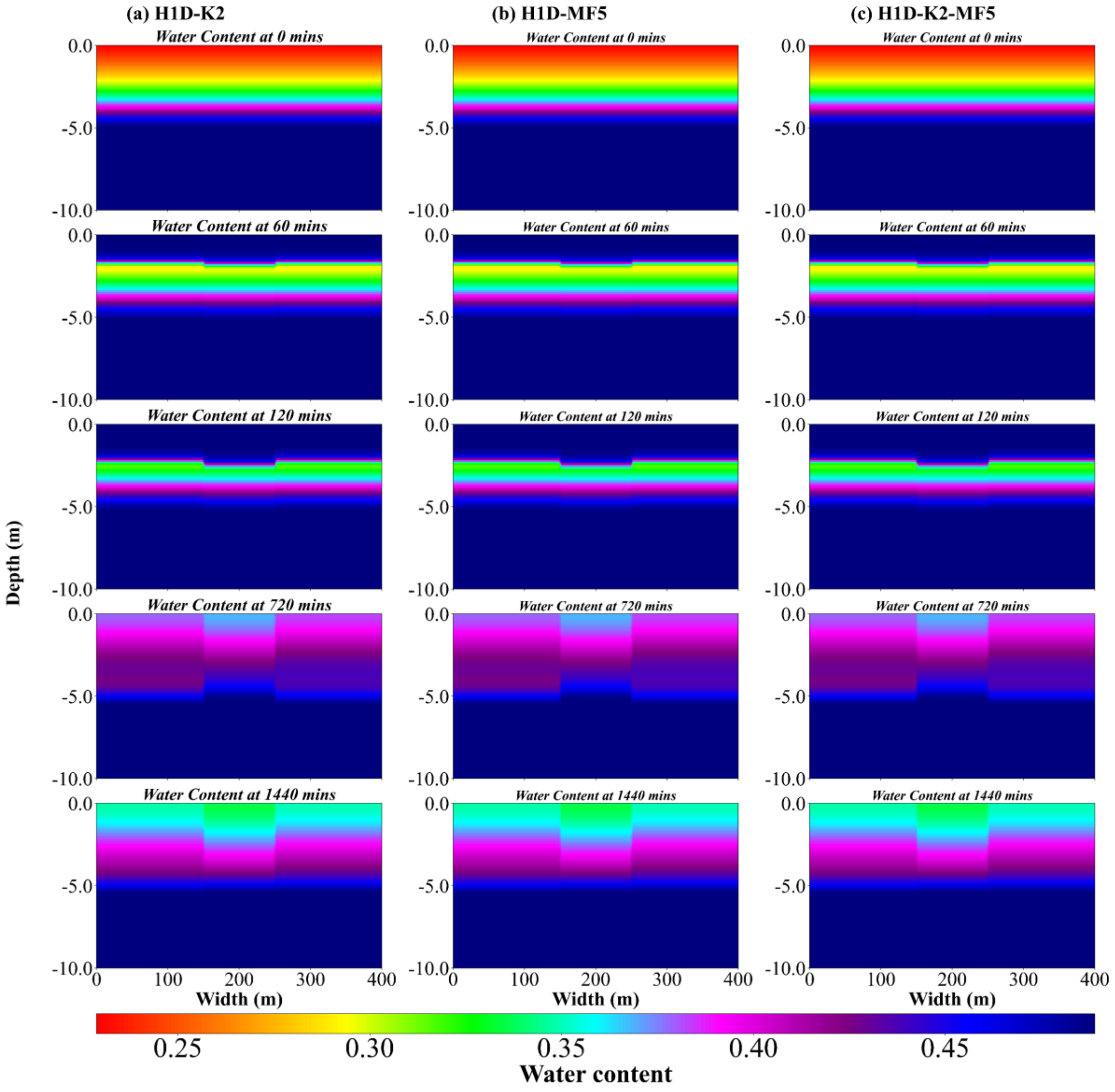


Table: Comparisons of water balance

		Elements	Values		Values
Surface and Vadose Zone	H1D-K2	Q in (m^3)	264000.00	H1D-K2-MF5	264000.00
		Q out (m^3)	47657.35		47657.35
		Q storg surf (m^3)	0.00		0.00
		Q storg sub (m^3)	135883.60		136564.10
		Q drain (m^3)	94583.55		93920.40
		Discrepancy (%)	**5.211**		**5.217**
Groundwater	H1D-MF5	Recharge In (m^3)	92968.20		93920.40
		Total In (m^3)	92968.20		93920.40
		Storage Out (m^3)	92968.20		93920.39
		Total Out (m^3)	92968.20		93920.39
		Discrepancy (%)	**1.61E-06**		**1.35E-05**

Results & Discussions: Benchmark Model

❑ Benchmark Model:

- MODPATH Version 7 model domain (Pollock, 2016)
- A complex model includes pumping, river, unconfined, & confined aquifer.
- The original model unit is an English unit (EU).

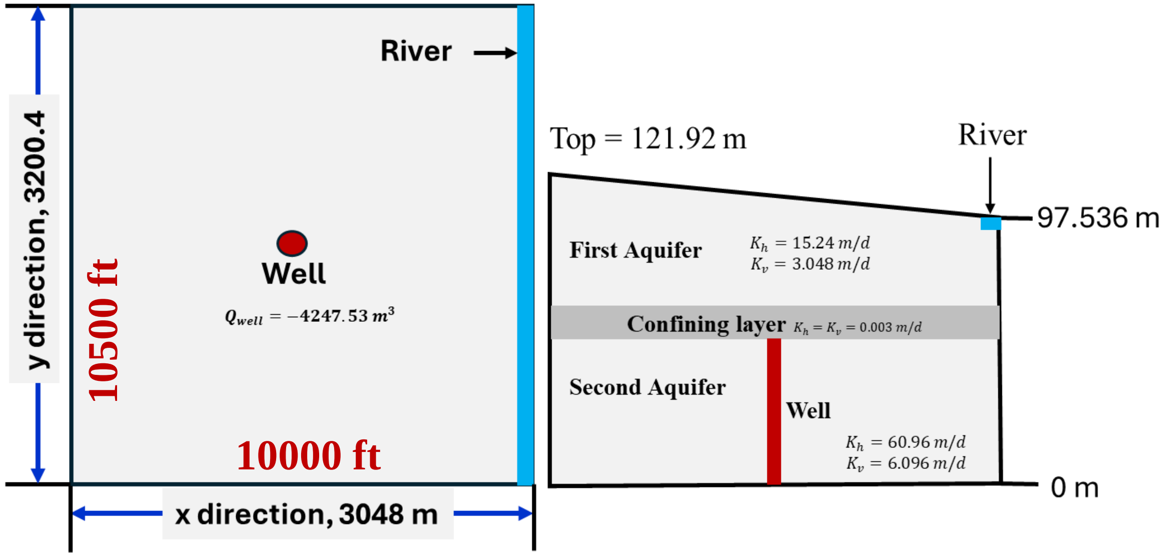


Fig. MODPATH Version 7 model domain after converting EU to SI unit.

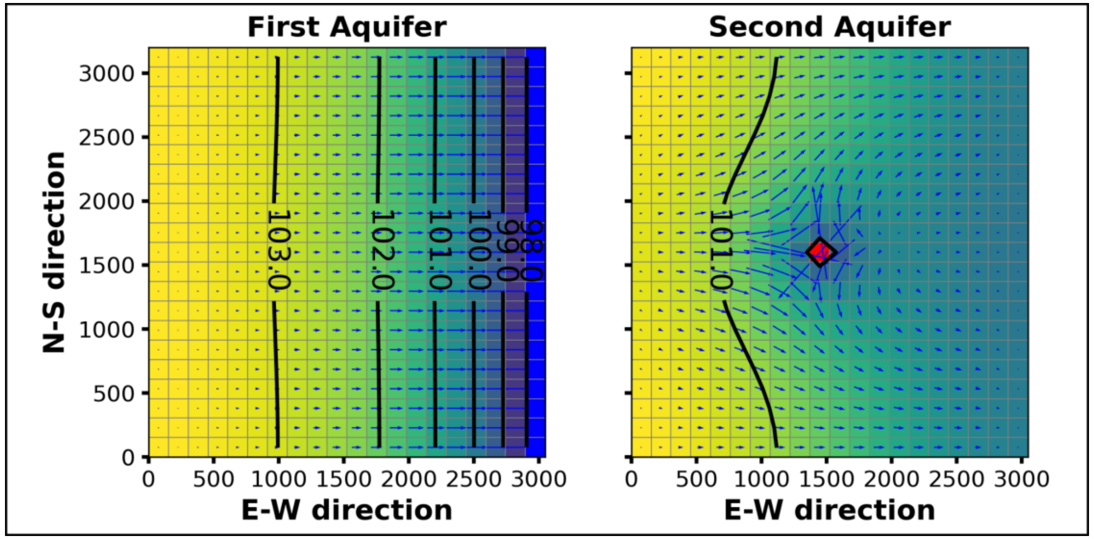


Fig. Groundwater head distribution after converting EU to SI unit for MODPATH Version 7 model domain

Recharge directly assigned to the cell

Table: Water balance comparisons after converting EU to SI

	Recharge In	Total In	Wells Out	River leakage Out	Total Out	In-Out	Discrepancy (%)
EU unit (ft^3)	525000.00	525000.00	150000.00	375000.00	525000.00	0.00	0.00
EU to SI Unit (m^3)	14866.34	14866.34	4247.53	10618.82	14866.34	0.00	0.00
SI Unit (m^3)	14866.34	14866.34	4247.53	10618.38	14865.90	0.44	0.00

Results & Discussions: Benchmark Model

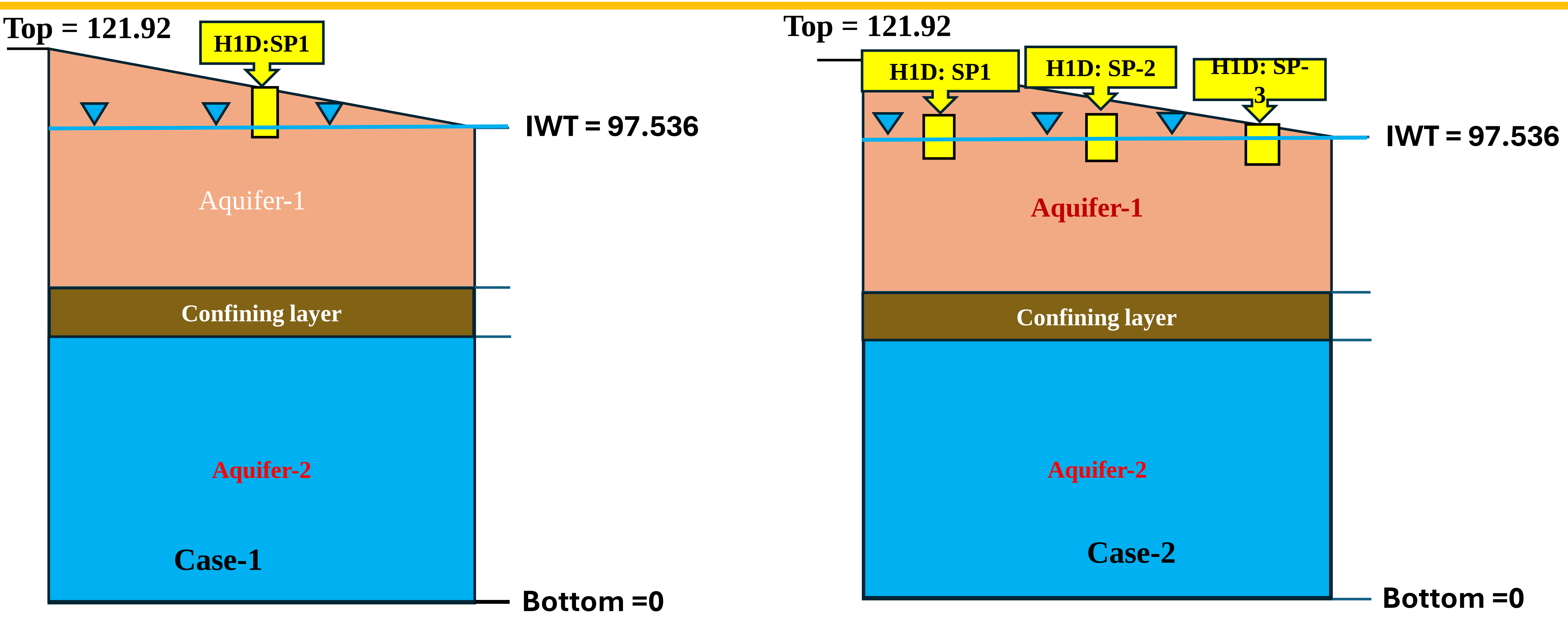


Fig. Number of H1D columns representing the unsaturated flow wedge in hillslope modeling to reproduce the steady state MODPATH reference simulation.

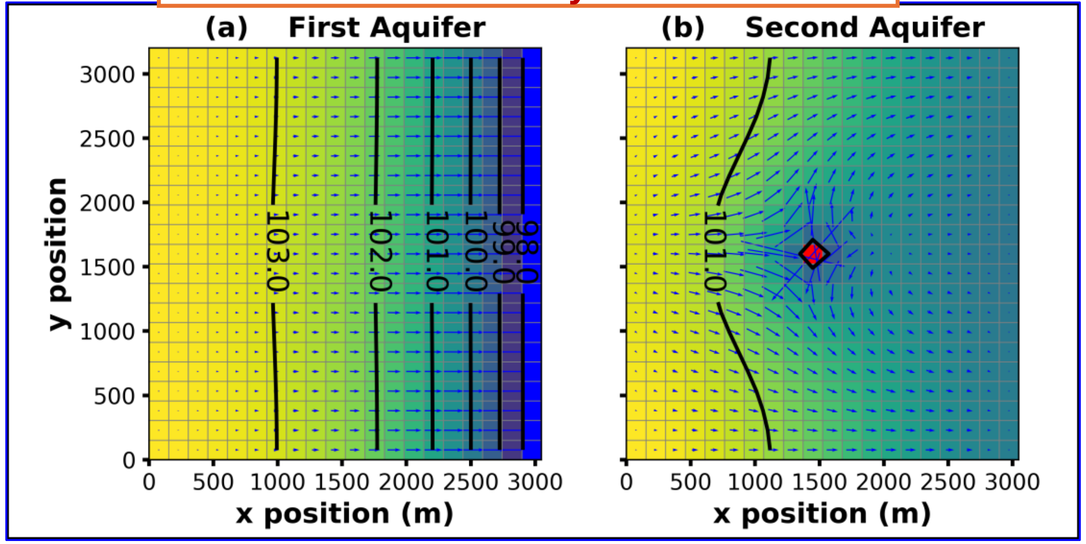
- **Hydraulic properties of material (sand):**

  θ_r = 0.01, θ_s = 0.30, α =3.3 (1/m), n = 4.1, k_s= 15.24 m/day, l = 0.5

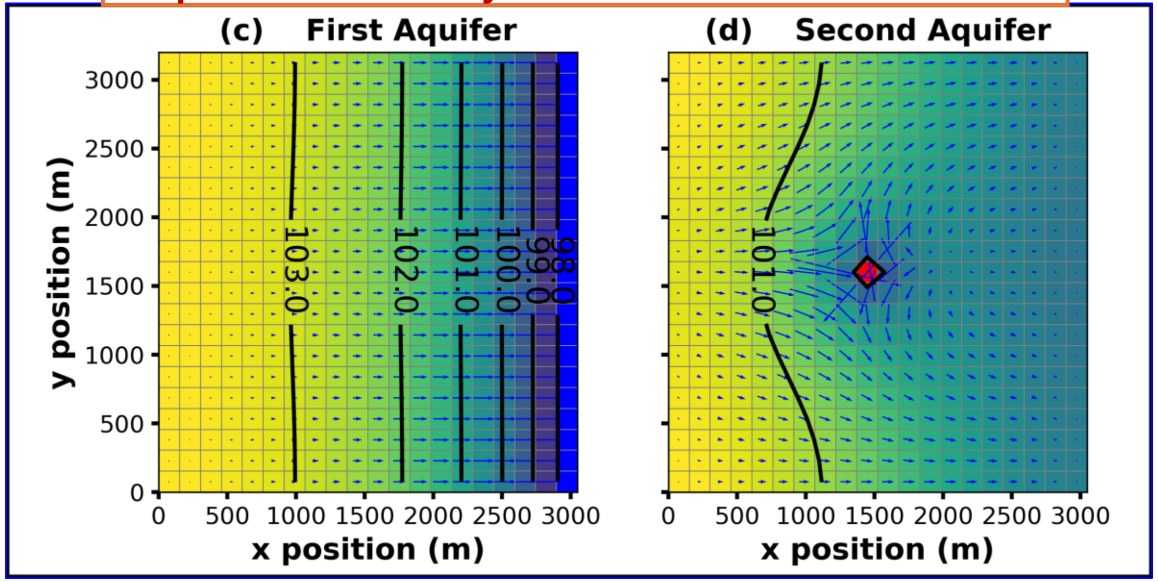
- H1D bottom = 20.0405 m
- Initial WTD in H1D = 12.192 m

Results & Discussions: Benchmark Model

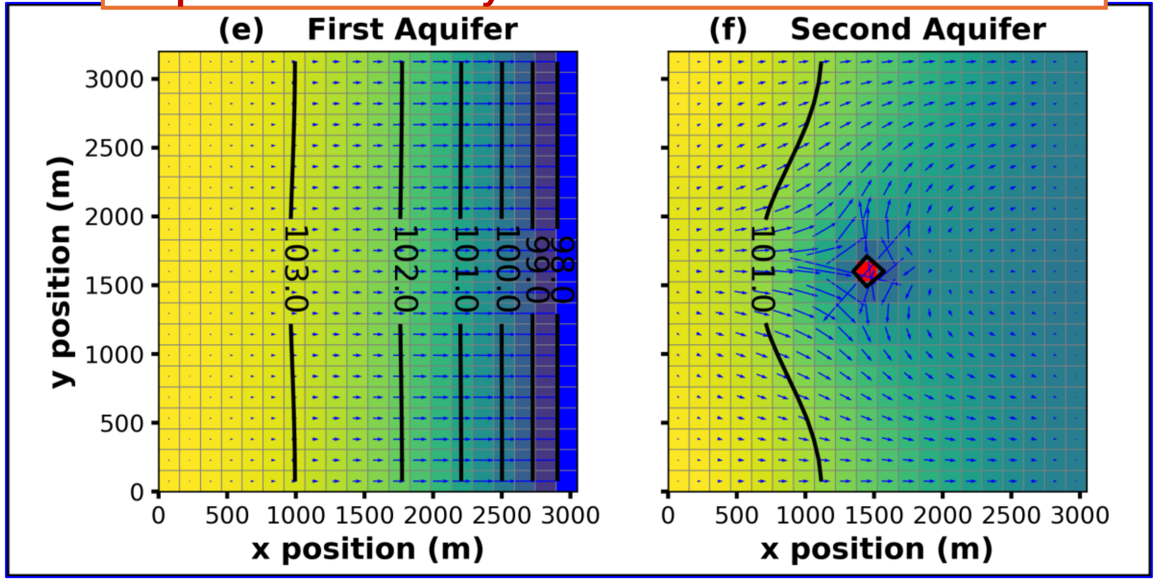
Reference Model Steady State Simulation



Coupled Model Steady State Simulation: 1 H1D Profile



Coupled Model Steady State Simulation: 3 H1D Profile



- **MODPATH model:**

  Head statistics:

  Min: 97.59; Max: 103.38; Std: 1.18

- **New coupled model 1 H1D profile:**

  Head statistics:

  Min: 97.59; Max: 103.38; Std: 1.18

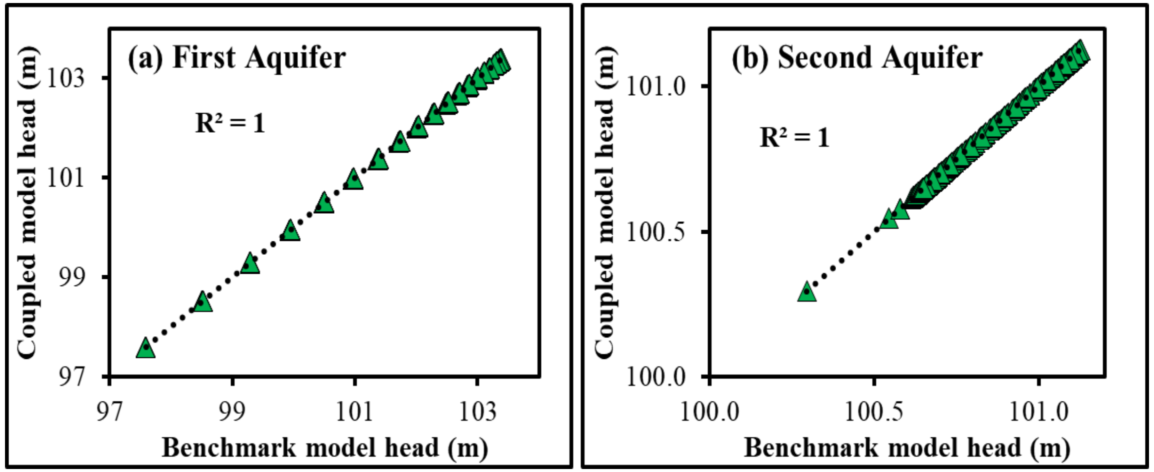
- **New coupled model 3 H1D profile:**

  Head statistics:

  Min: 97.59; Max: 103.38; Std: 1.18

Results & Discussions: Benchmark Model

Comparisons between new coupled model using one HYDRUS-1D profile and MODPATH model.



Comparisons between new coupled model using three HYDRUS-1D profile and MODPATH model.

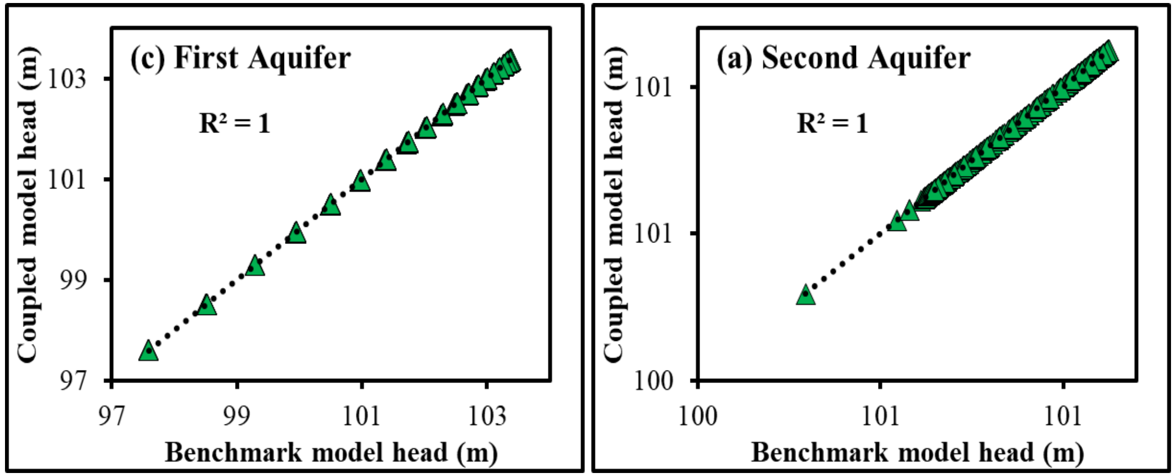


Table: Water balance comparisons between the new coupled model using 1 and 3 HYDRUS-1D profile with the MODPATH model.

	Recharge In	Total In	Wells Out	River leakage Out	Total Out	In-Out	Discrepancy (%)
MODPATH (m^3)	14866.34	14866.34	4247.53	10618.82	14866.34	0.00	0.00
H1D-K2-MF5, 1 H1D (m^3)	14866.34	14866.34	4247.53	10618.37	14865.90	0.44	0.00
H1D-K2-MF5, 3 H1D (m^3)	14866.34	14866.34	4247.53	10618.37	14865.90	0.44	0.00

Results & Discussions: Steady & Transient MODPATH domain

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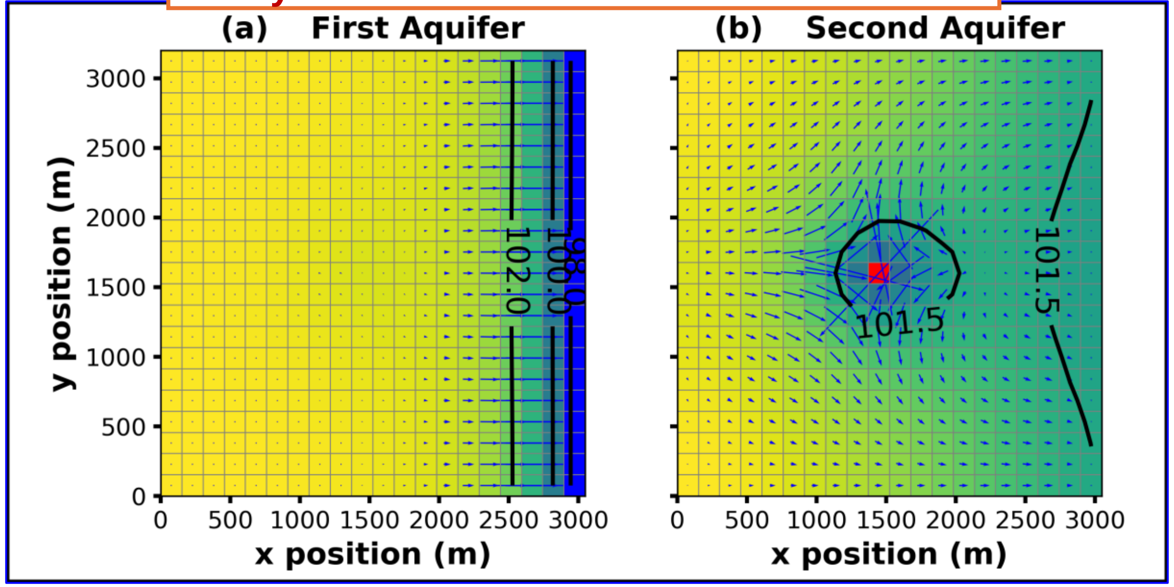
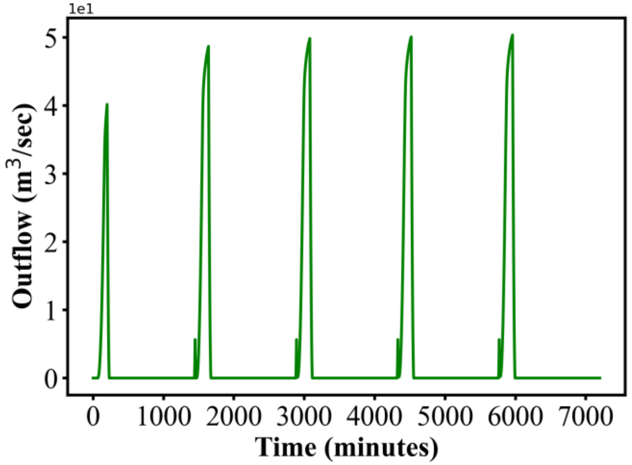
Steady State Simulation: GW head distribution

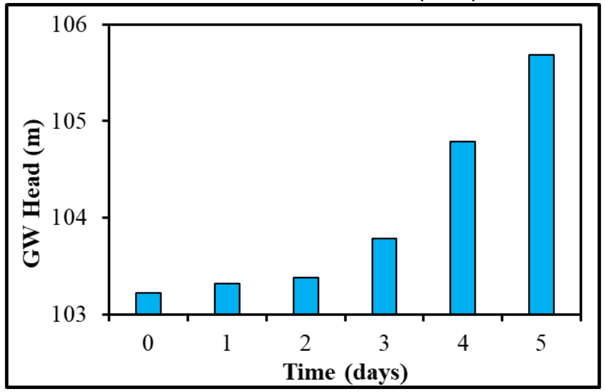


Transient Simulation

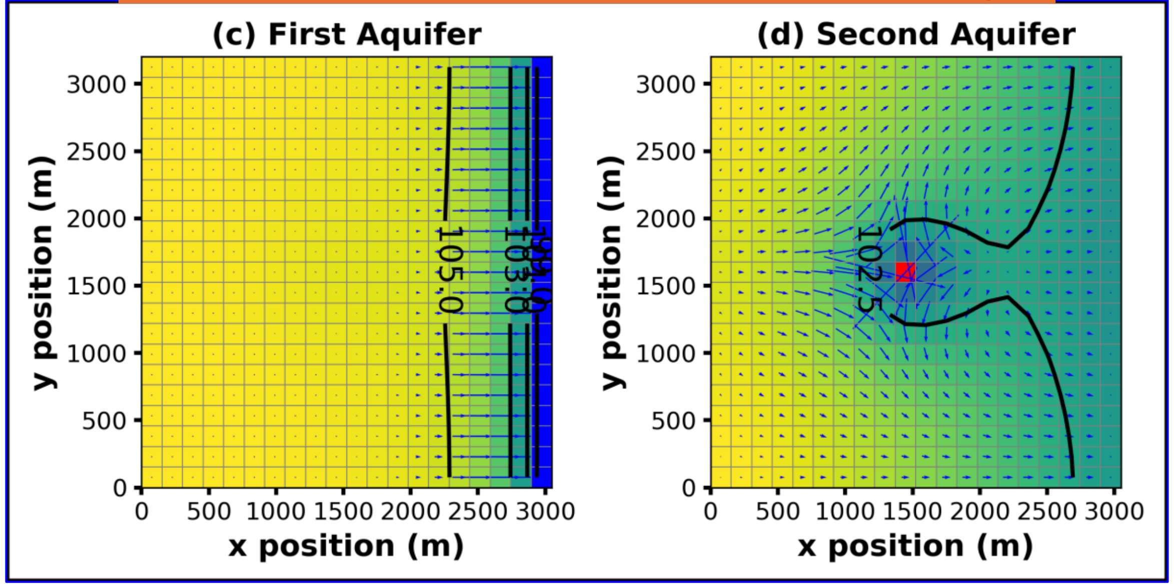
Overland flow



GW head at (0,0) cell



Transient Simulation: GW head distribution at day 5



Transient Water Balance:

Surface & vadose zone		Groundwater	
Q in (m^3)	16095452.0	Storage In (m^3)	35947.47
Q out (m^3)	4270139.04	Recharge In (m^3)	9310275.80
Q storg_surf (m^3)	0.00	Storage Out (m^3)	8902028.16
Q storg_sub (m^3)	7779370.76	Well Out (m^3)	42475.30
Q drain (m^3)	4655137.30	River leakage Out (m^3)	401602.32
Discrepancy(%)	**3.71**	**Discrepancy(%)**	**1.20E-3**

Take Home

- A python-based multi-model framework is established by accurately coupling HYDRUS-1D, KINEROS2, & MODFLOW-2005.
  - The new externally coupled model (H1D-K2-MF5) performs almost identically to the established simulation codes for a number of benchmark simulation cases.
  - The new model is computationally efficient compared to integrated watershed models.
- The multi-model framework is flexible:
  - H1D-K2 for overland flow and vadose zone simulation.
  - H1D-MF5 for groundwater simulation.
  - H1D-K2-MF5 for Surface and Sub-surface processes.

- The new model is an ideal tool for large-scale surface-subsurface simulation.

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Thank you


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