

Optimizing Managed Aquifer Recharge (MAR) at a Hillslope Scale in California's Central Valley

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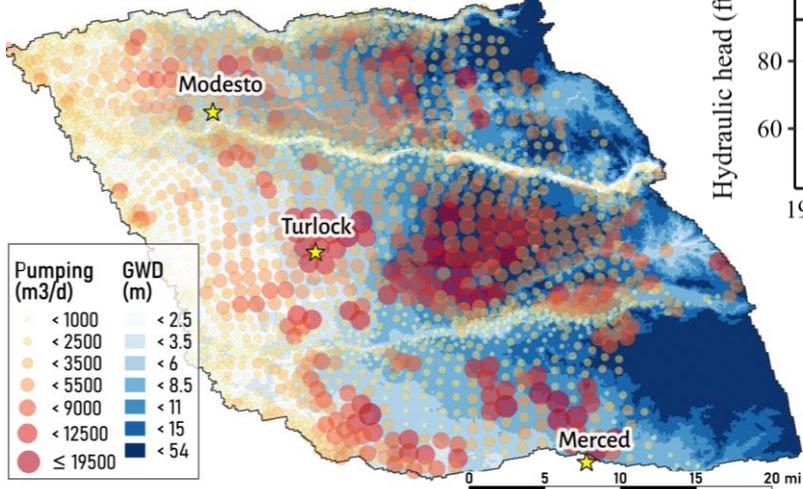
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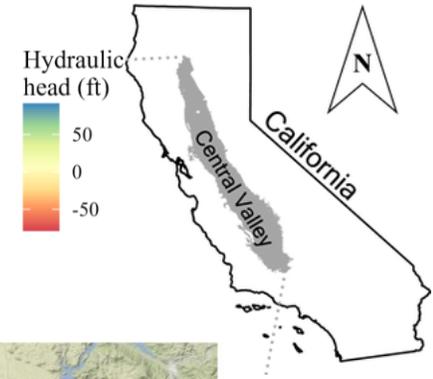
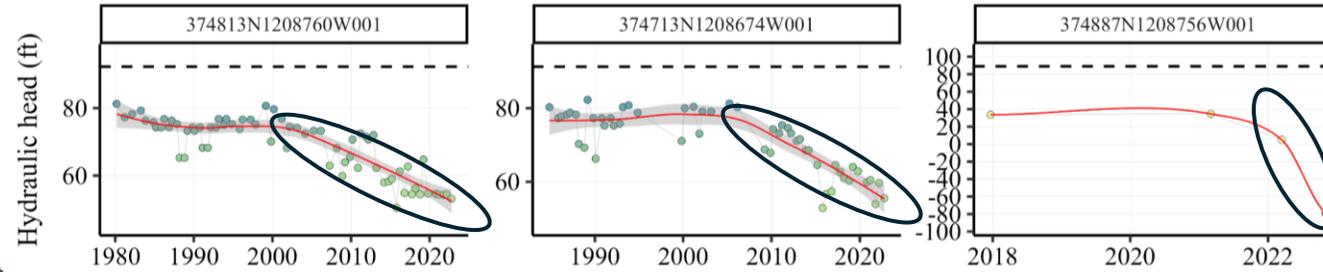
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Continuous groundwater decline and severe environmental issues

Average GWD (1995-2003)

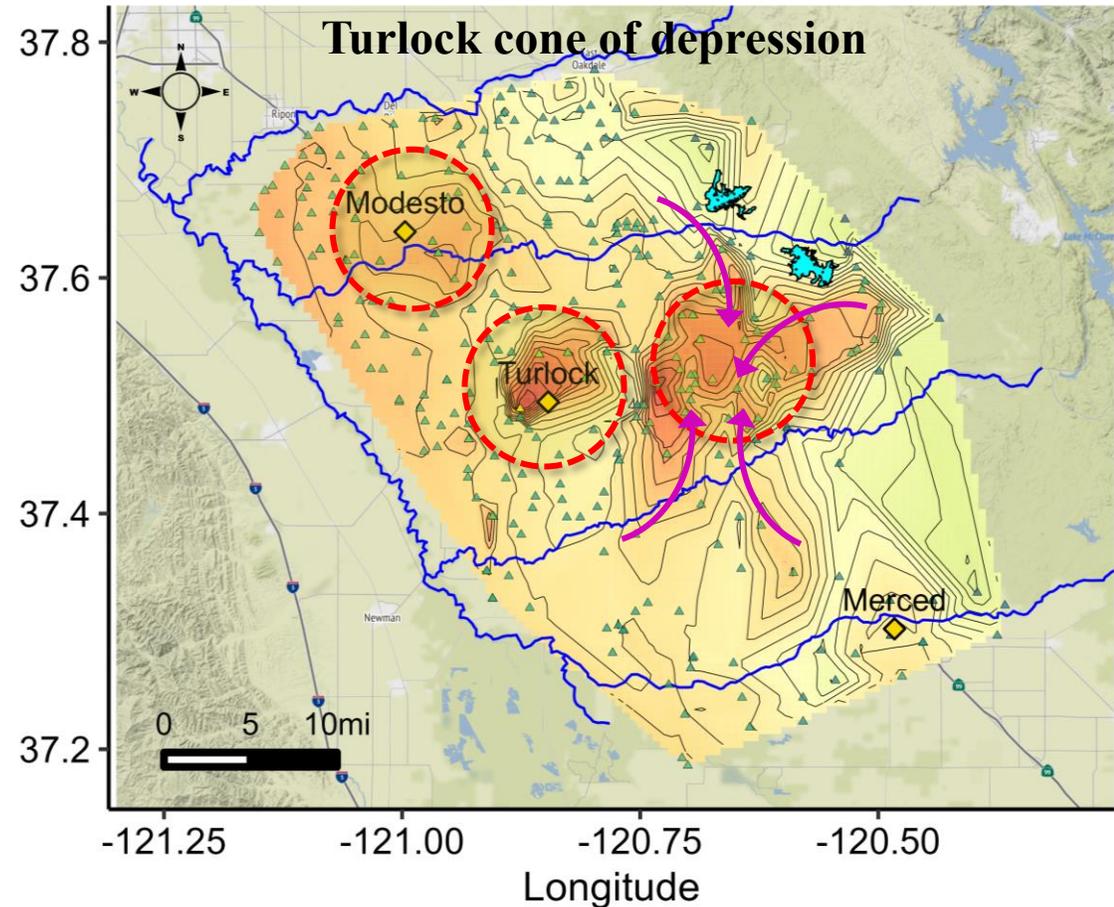


(Alberto et al., 2025)



Source: Levy et al. (2021)

- Pumping & excessive groundwater exploitation in Turlock, Modesto, and part of Merced subbasins.
- Hydraulic head (2022) dropped almost 100 ft
- Cone of depression in Turlock
- Severe environmental issues & water unsustainability
- To better understand the groundwater dynamics impacted by pumping activities, to mitigate the influence of pumping wells, to test the application of MAR in Central Valley



Managed Aquifer Recharge (MAR)

MAR

- Surface MAR (Flood-MAR & Ag-MAR)
- Infiltration basins (ponds/tanks)
- Dry wells/vadose zone wells
- ASR (injection wells)

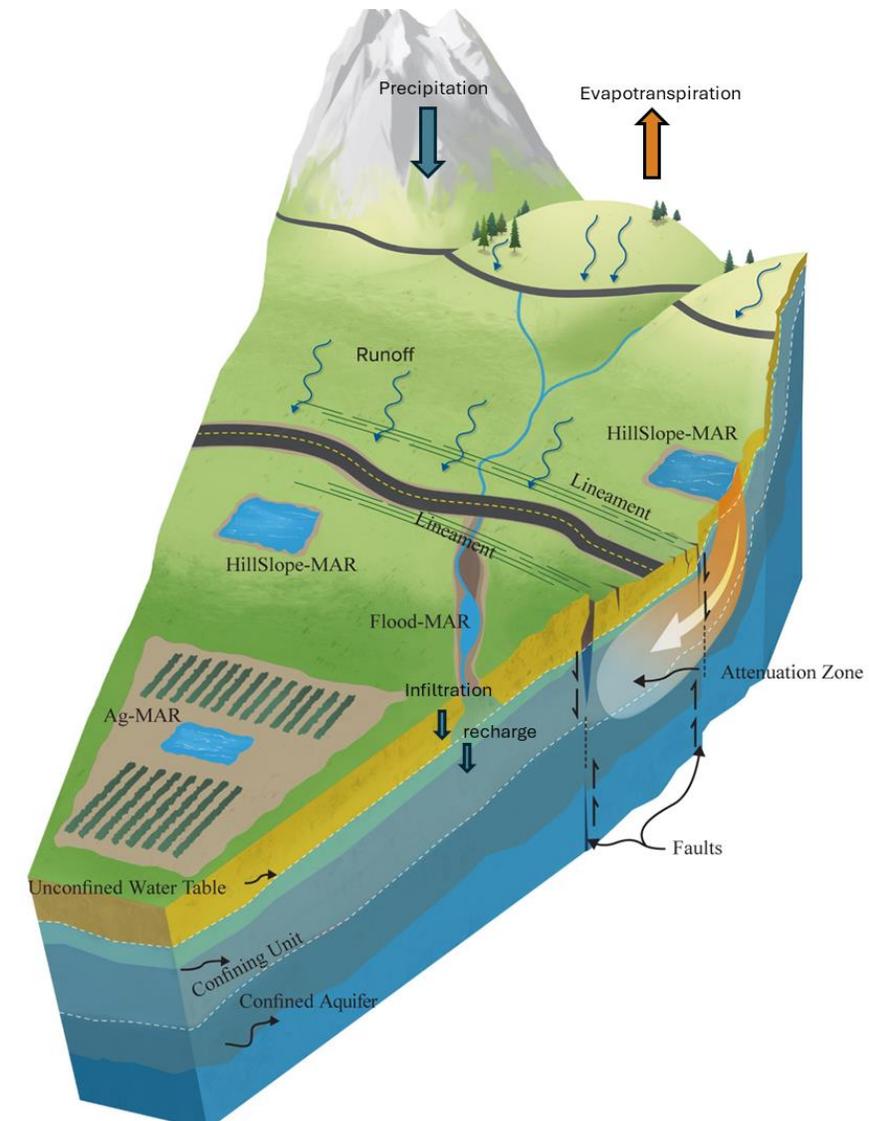
Advantages

- replenishing groundwater resources
- enhancing water security
- mitigating the impacts of droughts and over-extraction
- Environmental sustainability

&

Challenges

- Uncertain bio-geophysical processes
- Complex subsurface flow dynamics and heterogeneity
- Possible water contamination
- Mainly applied at flat terrains
- **Understanding and applying hillslope MAR remains unknown**



hydrological cycle in mountain-hillslope-valley system

Scientific questions & Objectives

- **Where is the best location to pump groundwater to minimize the impact on groundwater system without compromising the exploitation efficiency?**
 - **Where is the best location to apply MAR? Is the best location the same for Ag-MAR, dry well-MAR, and injection wells?**
-
- Surface water-UZ-SZ dynamics and interactions
 - Hydrological cycle in hillslope systems
 - Pumping well impacts on groundwater dynamics
 - Application of MAR in hillslope-valley floor-river valley systems
 - Sensitivity of slopes, K, and bedrock shapes to groundwater movements

Experimental study area in California's Central Valley

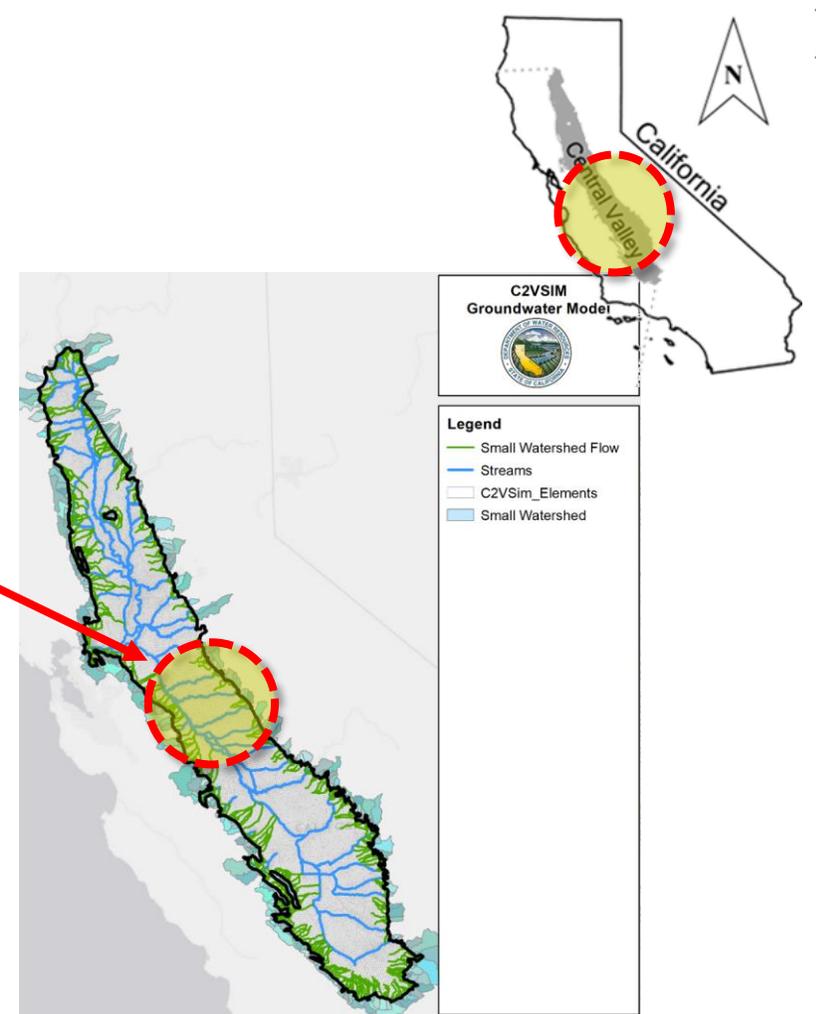
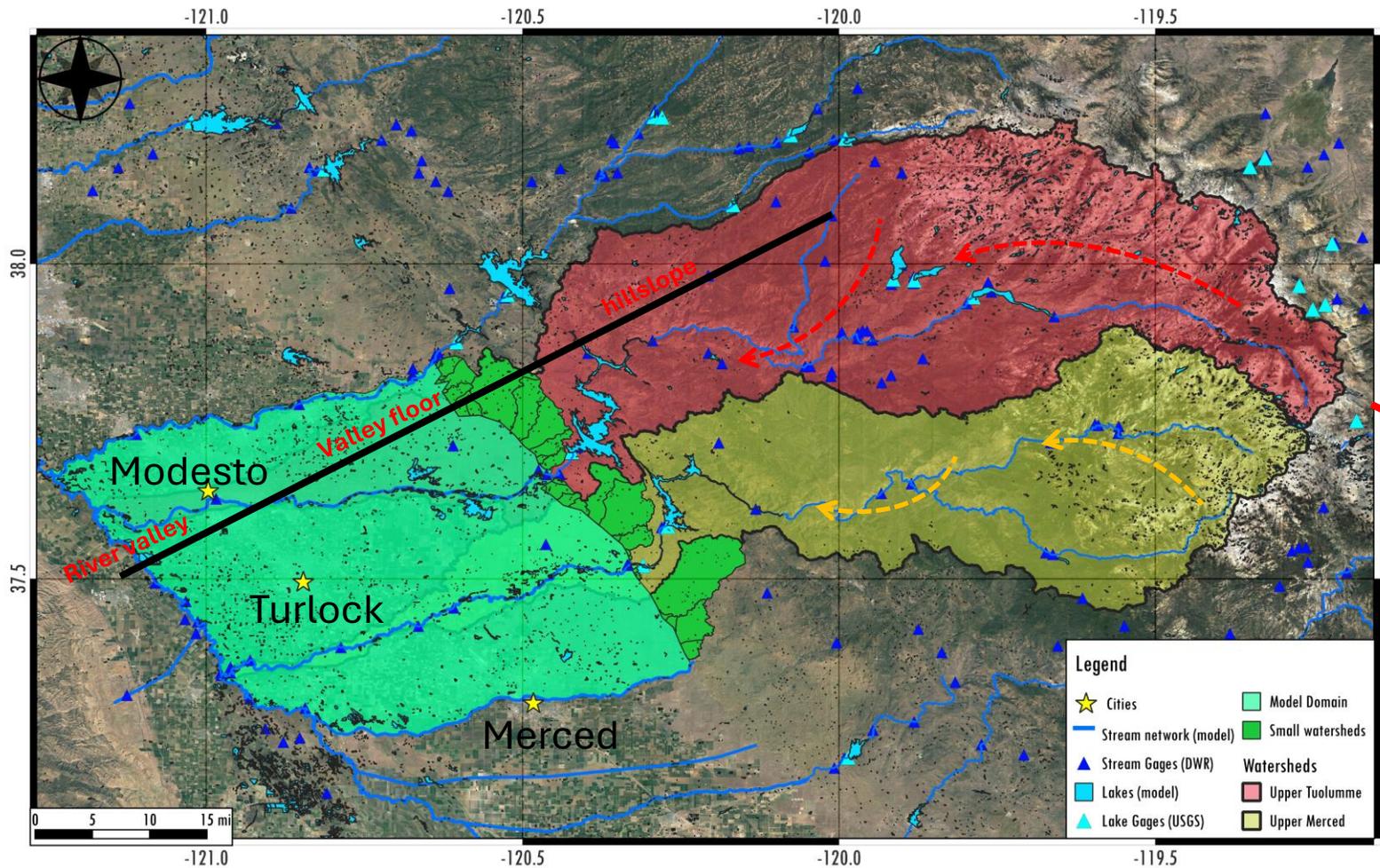
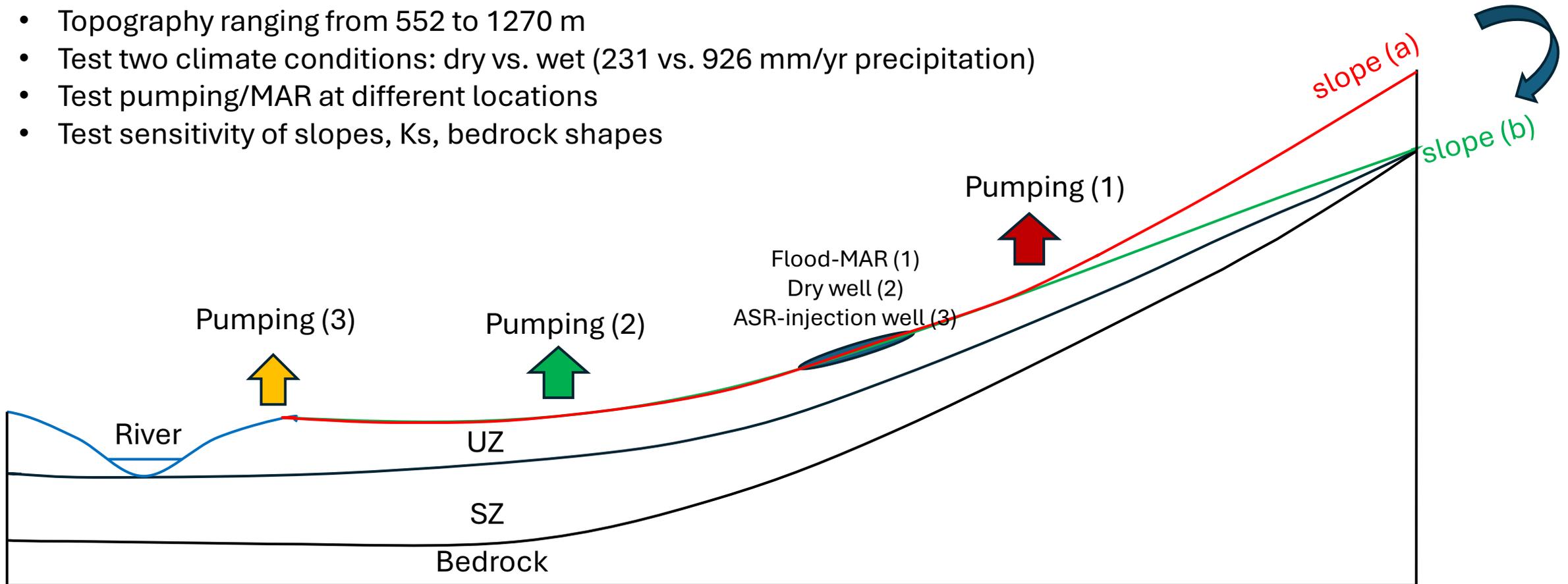


Fig 1. c2vSIM Model area showing small watersheds areas contributing baseflow and runoff to GW/SW (DWR, 2018).

Cross-section covering hillslope-valley floor-river valley
 Build a conceptual model representing part of the Central Valley

Theories & Methods

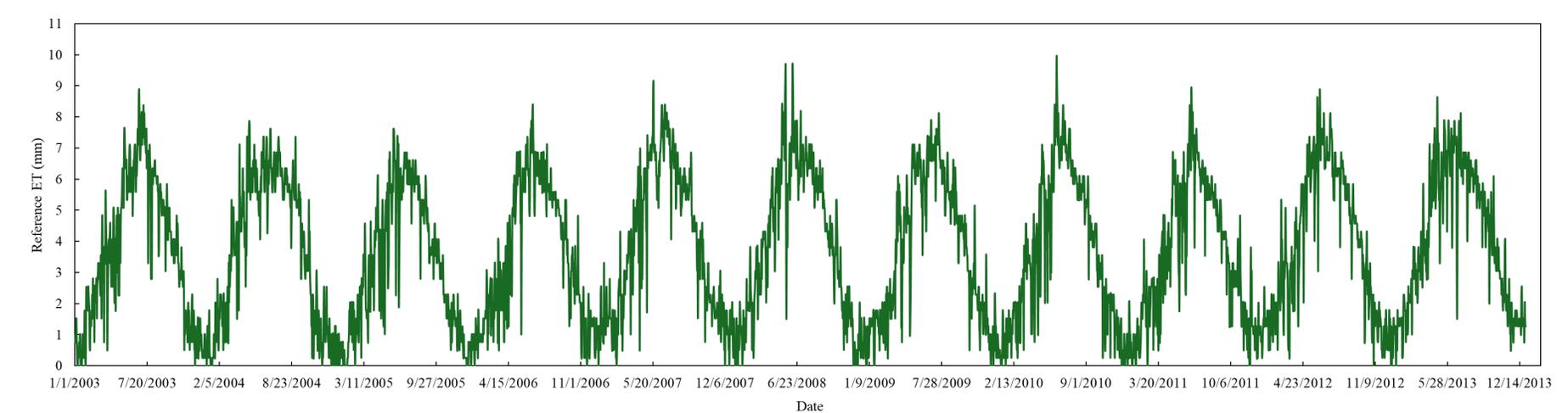
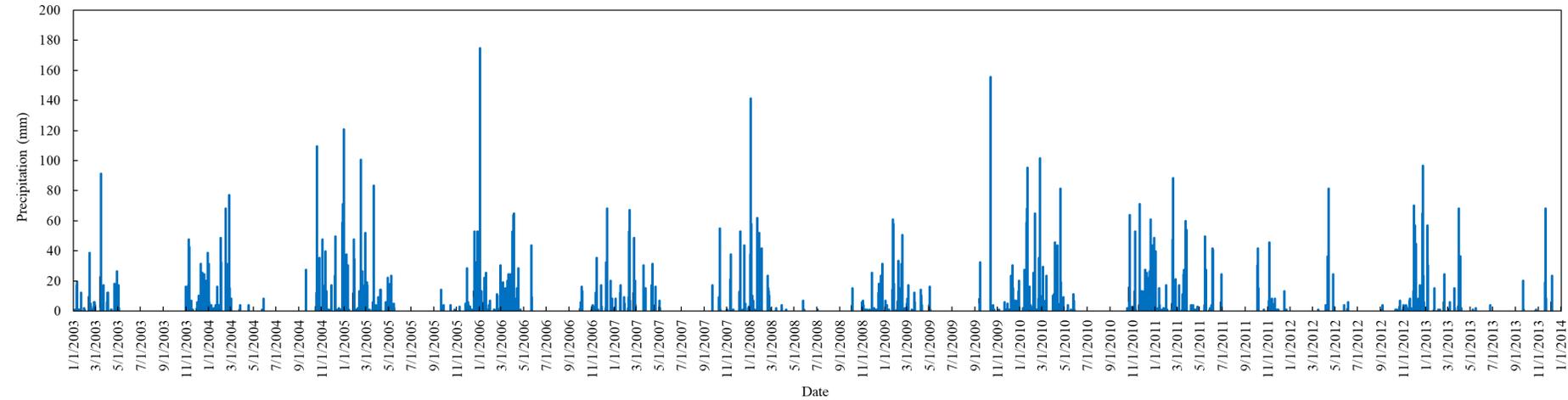
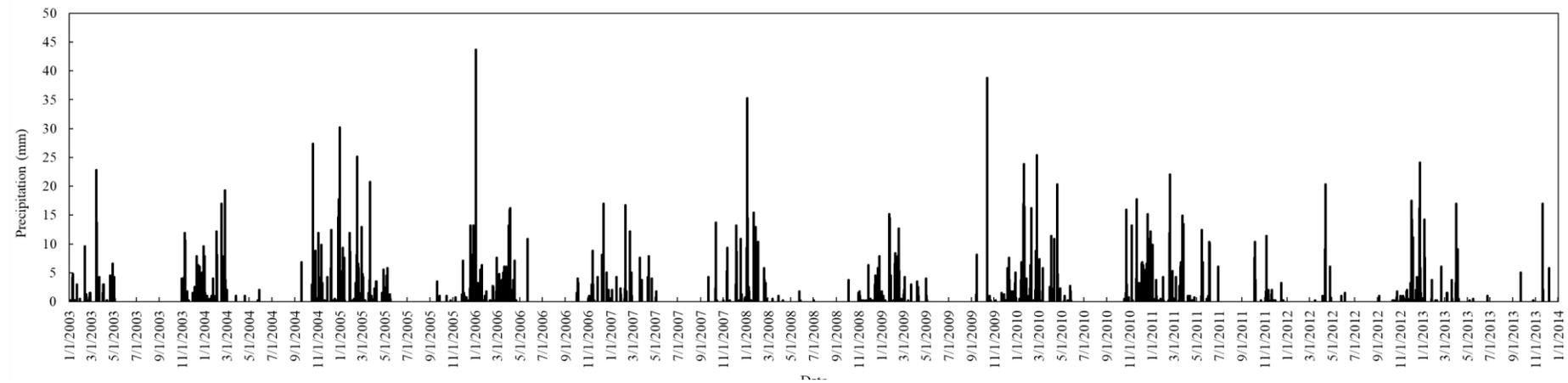
- **Technique:** MIKE SHE- integrated surface water-UZ-SZ hydrological model
- 100 m × 100 m grid cells
- 6000 × 1200 m² model domain
- Hillslope-valley floor-river valley system
- Topography ranging from 552 to 1270 m
- Test two climate conditions: dry vs. wet (231 vs. 926 mm/yr precipitation)
- Test pumping/MAR at different locations
- Test sensitivity of slopes, Ks, bedrock shapes



Conceptual model of hillslope MAR application

Climate Data

- **Simulation period:**
01/01/2003-12/31/2013
- **Dry condition**
(231 mm/yr precipitation)
- **Wet condition**
(926 mm/yr precipitation)
- **Reference ET**
(1346 mm/yr precipitation)



MIKE SHE integrated surface water-UZ-SZ hydrological modeling

Numerical Modeling & governing equations

- **Surface water:**

Saint-Venant Equations (**1D** unsteady open channel flow)

Continuity:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_L$$

Momentum:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^2}{A} \right) + gA \frac{\partial h}{\partial x} + gQ|Q|/(C^2 AR) = 0$$

2D Overland Flow (Diffusive Wave) $\frac{\partial h}{\partial t} = \nabla \cdot (D(h)\nabla h) + r$

- **UZ:**

Rechard's equation (**1D** vertical variably-saturated flow)

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

- **SZ:** **3D** Groundwater Flow Equation (Darcy's Law with continuity)

$$S_s \frac{\partial h}{\partial t} = \nabla \cdot (K\nabla h) + R$$

Preliminary results

- Spin-up time required to reach steady-state under dry vs. wet conditions
- Water balance/water partitioning under dry vs. wet conditions
- Impacts of pumping wells & resulting cone of depression
- Impacts of injection well MAR on groundwater levels

Water partitioning and spin-up time under dry vs. wet conditions

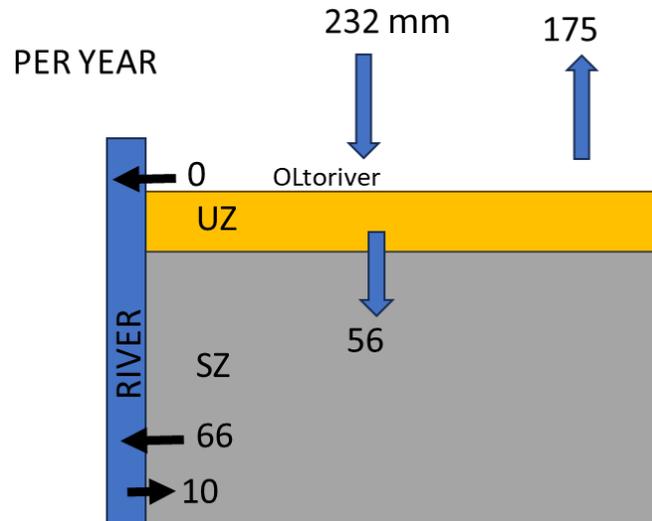
- Spin-up time to steady-state under dry conditions: 170 years
- Spin-up time to steady-state under wet conditions: 70 years

Dry condition:

76% lost by ET

24% recharge to groundwater

no overland flow



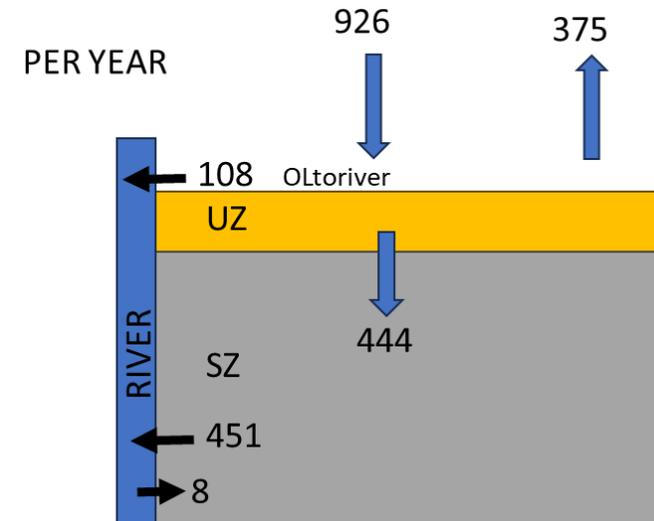
Water balance at dry conditions

Wet condition:

40% lost by ET

48% recharge to groundwater

12% overland flow to river



Water balance at wet conditions

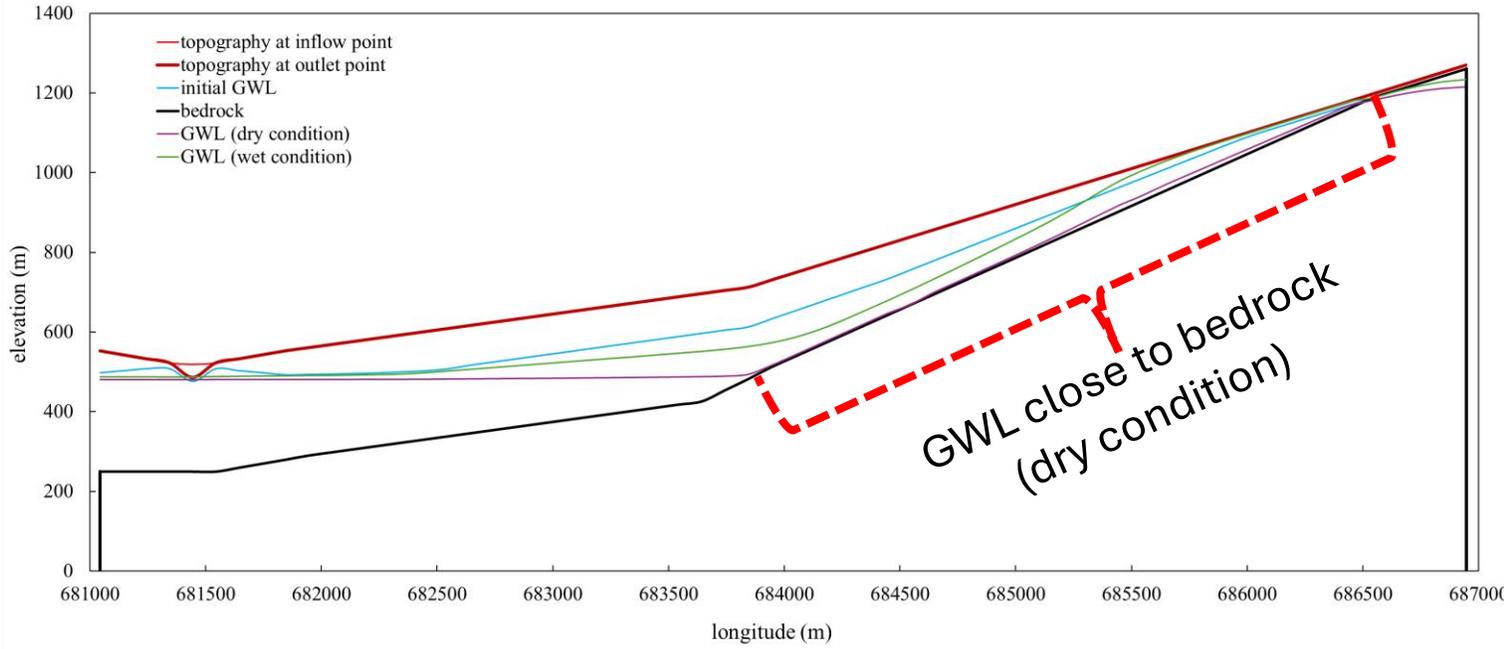
- **River discharge under dry condition:**

seasonal trend (475,855 m³/yr baseflow contributes to river, while 59 m³/yr overland flow contributes to river) **8065:1**

- **River discharge under wet condition:**

seasonal trend & response to rain event 4:1
 (3,248,509 m³/yr baseflow contributes to river, while 775,636 m³/yr overland flow contributes to river)

- Under dry condition, aquifer at hillslope mostly drained out with this steep slope.



Groundwater level (dry vs. wet condition)

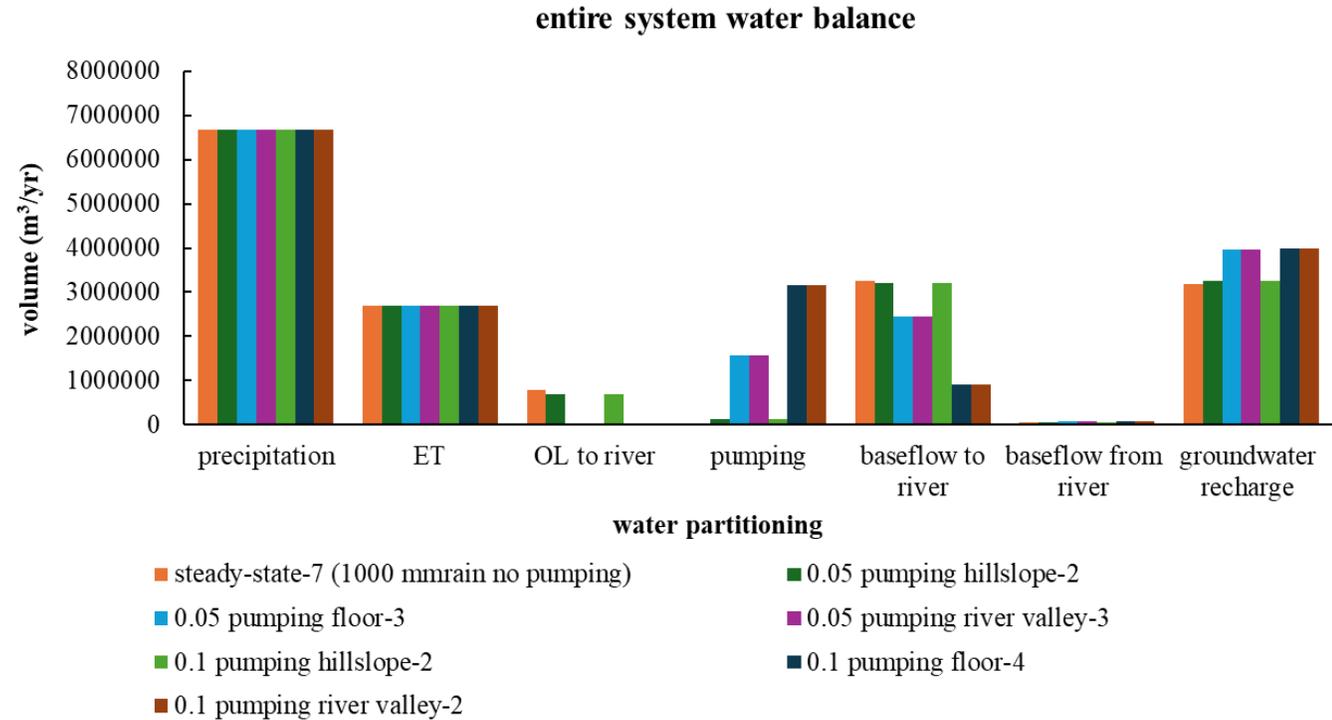


River discharge

Pumping at different locations & different rates

Conditions

1. no pumping
2. pumping at hillslope (0.05 vs. 0.1 m³/s)
3. pumping at valley floor (0.05 vs. 0.1 m³/s)
4. pumping at river valley (0.05 vs. 0.1 m³/s)



Water Balance Results

- **Pumping at hillslope:** inefficient for groundwater extraction (due to the thin aquifer).
- **Pumping at valley floor and river valley is more efficient**, yielding 1,577,585 m³ at a rate of 0.05 m³/s and 3,155,171 m³ at a rate of 0.1 m³/s.
- Pumping at valley floor and river valley consumes **most of overland flow and a portion of the baseflow** to the river. At a rate of 0.1 m³/s, it draws more baseflow compared to at 0.05 m³/s.
- Pumping at the valley floor and river valley contributes to **an increase in the groundwater recharge** component.

Cones of depression (steady-state GWL after pumping (0.1 m³/s))

Results

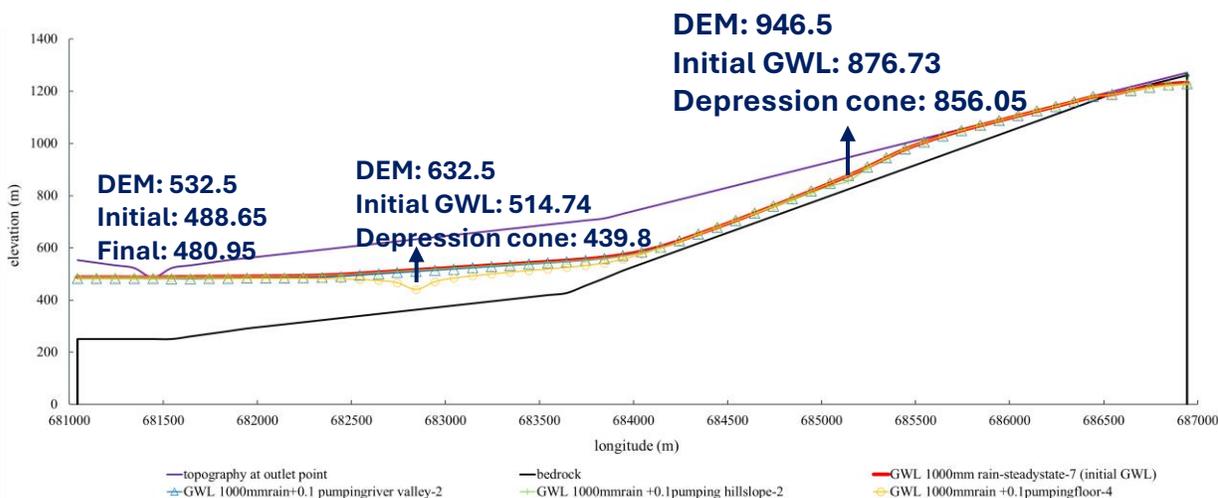
- **Cones of depression** at hillslope (**21m**) and valley floor (**75m**)
- **Slight regional groundwater drawdown at river valley (8 m)** due to strong hydraulic interactions near the river
- Less impact on groundwater drawdown and extent of cone of depression when pumping at 0.05 m³/s compared with 0.1 m³/s.

Suggestions

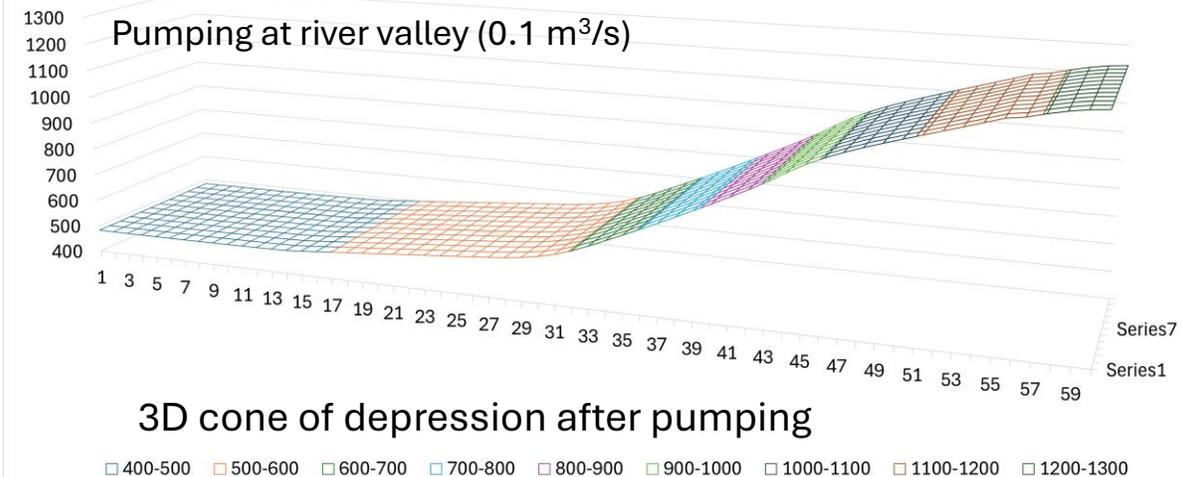
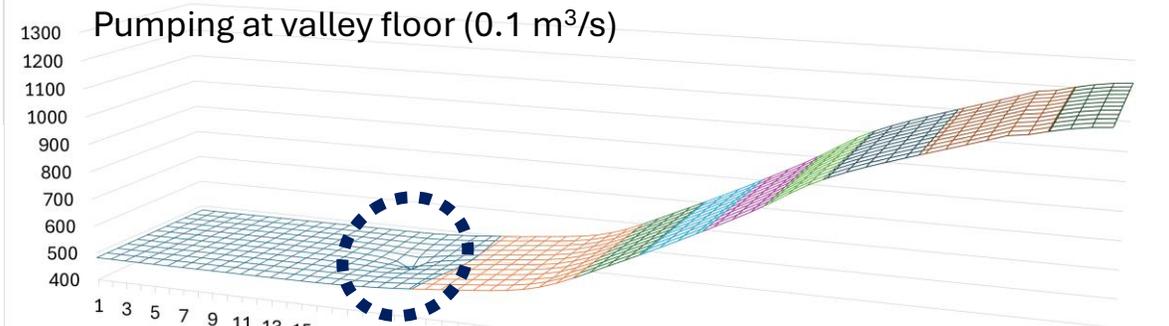
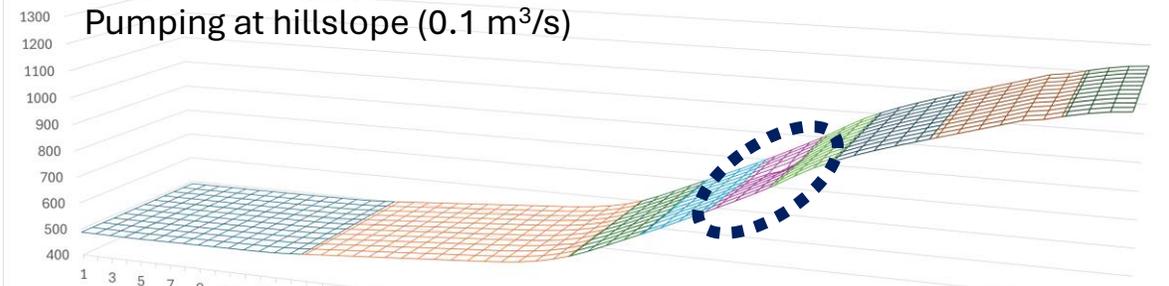
- Pumping at valley floor or **river valley** is generally effective and efficient.

slight GWL drawdown at river valley with limited pumping rate

replenish by the right-sided incoming water from hillslope

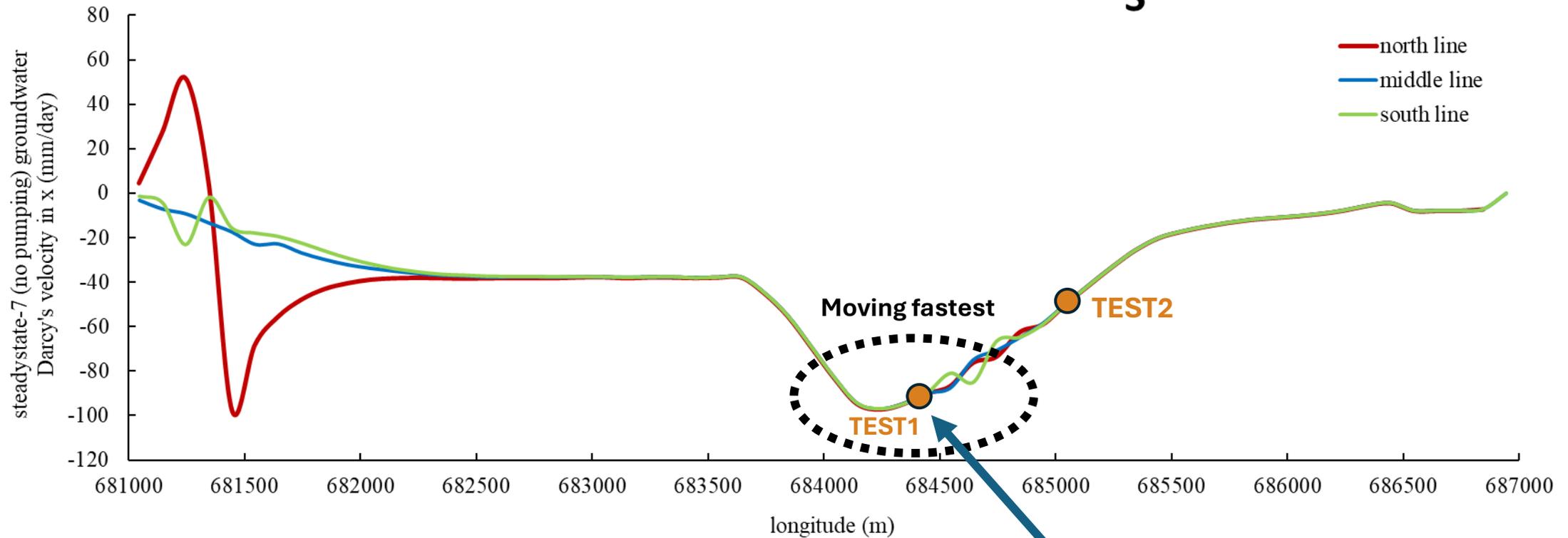
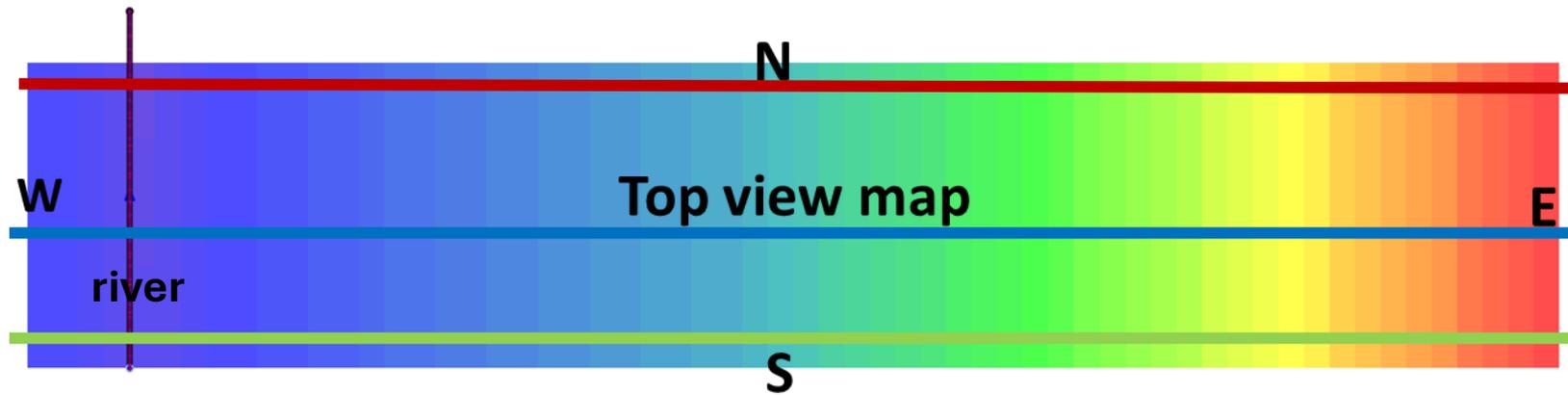


2D cross-section after pumping



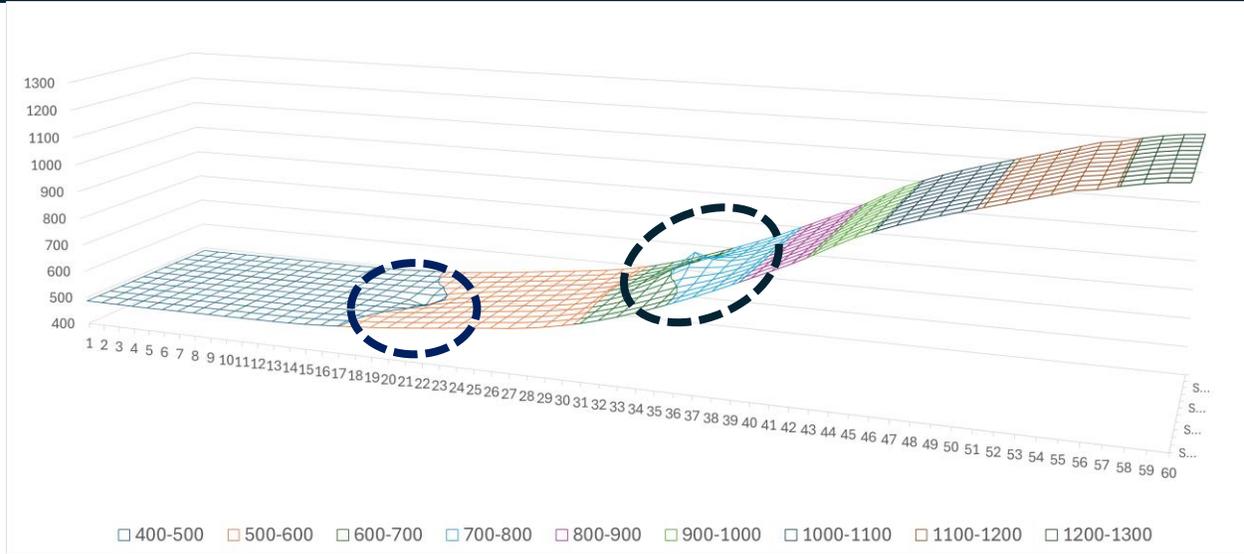
Groundwater migrate velocity

(steady-state status without pumping)



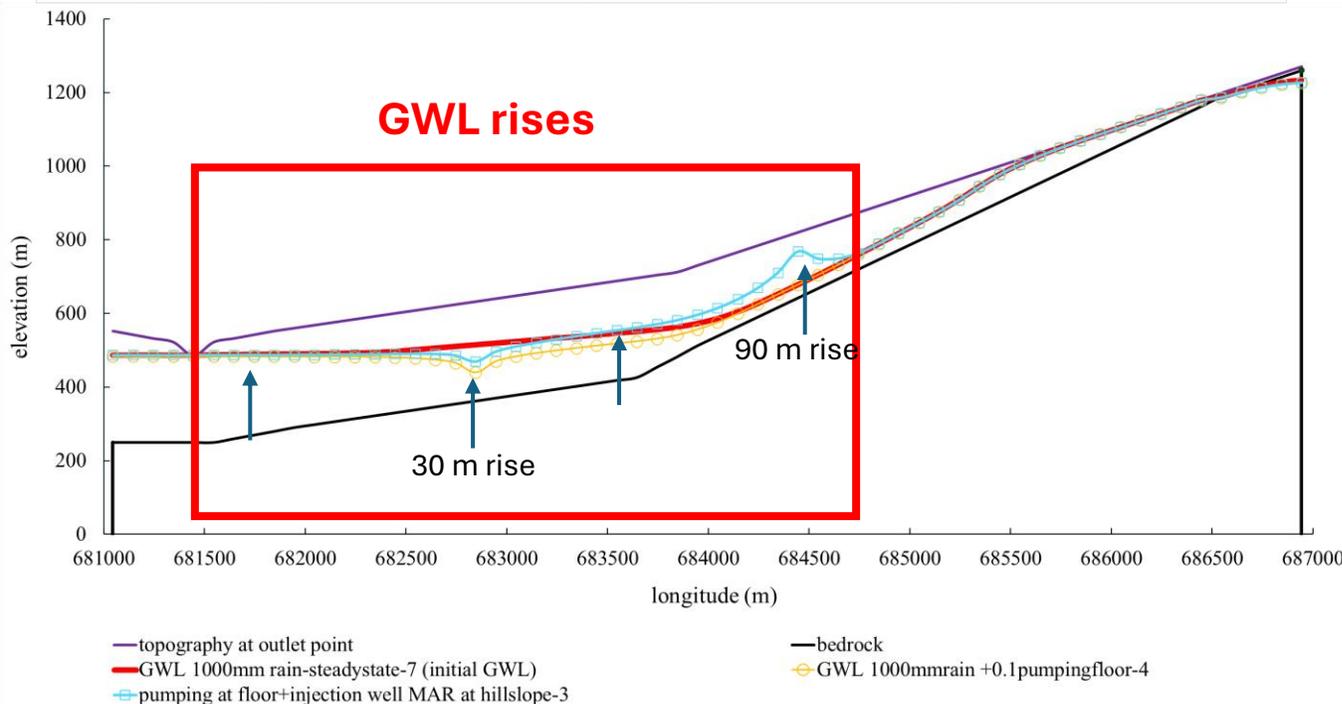
Is here a good position to apply MAR?

Pumping at valley floor + MAR at hillslope (lower part)



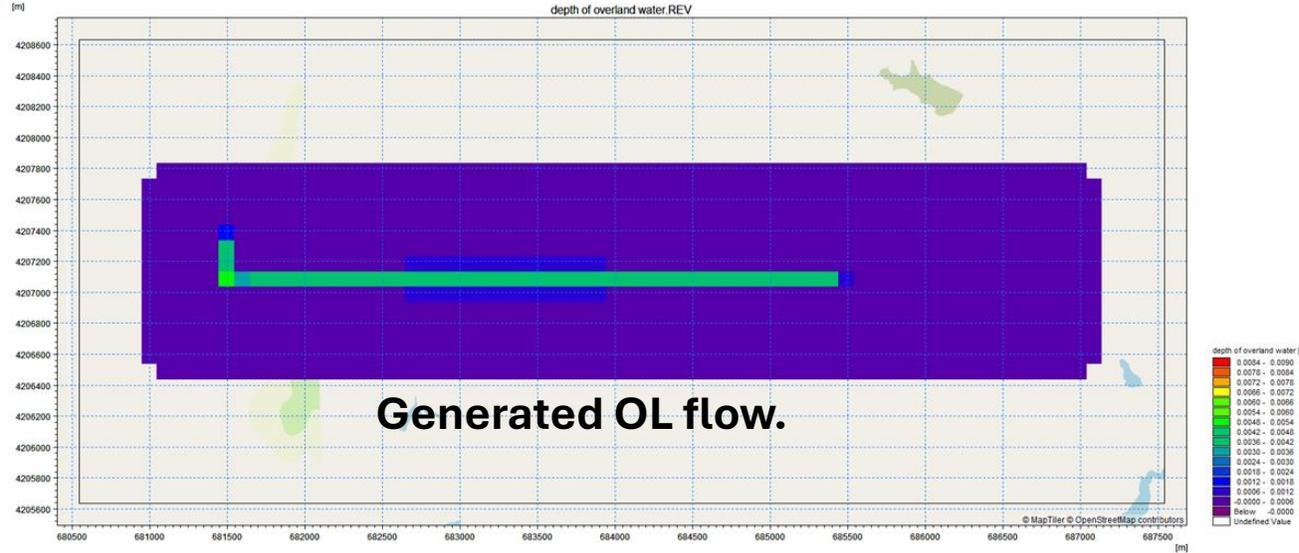
TEST1: pumping at floor (0.1 m³/s) + injection well MAR at the lower part of hillslope

- Cone of **depression** at valley floor
- Cone of **ascent** at hillslope (asymmetric)
- Managed Aquifer Recharge (MAR) at the hillslope **increases the groundwater level (GWL)** in the left region between the injection and pumping wells—extending even to the left side of the pumping well.
- MAR at hillslope does not significantly raise the GWL at the higher elevations of the hillslope



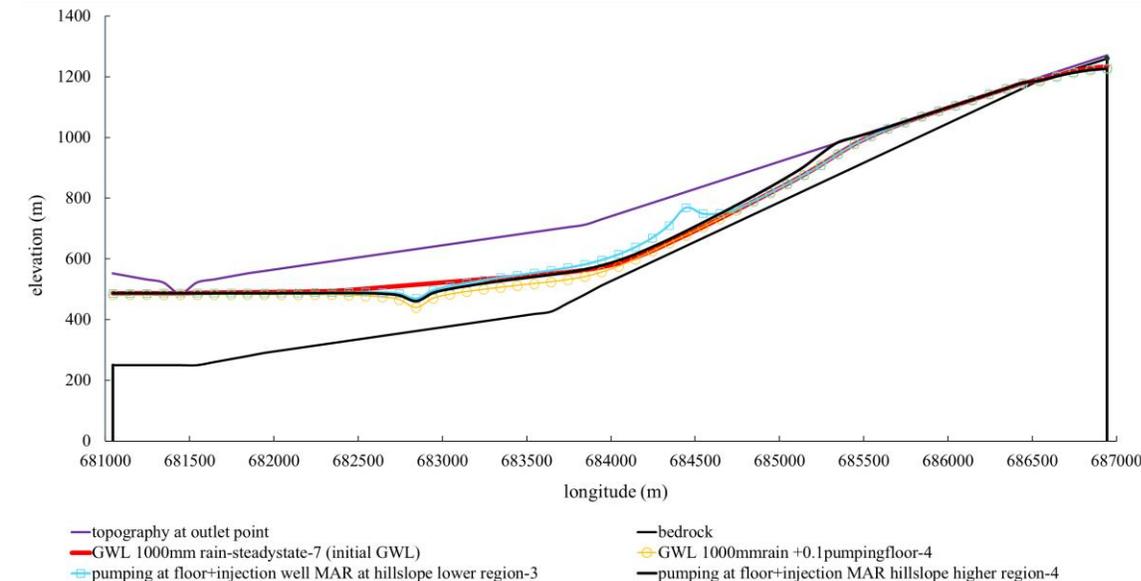
Cross-section groundwater level

Pumping at valley floor + MAR at hillslope (upper part)



TEST2: pumping at floor (0.1 m³/s) +injection well MAR at the upper part of hillslope

- **Generates overland water**, increased ET, waste of water resources. Not efficient for replenishing groundwater storage.
- The increase of GWL is smaller in this scenario compared to installing the injection well MAR at lower part of hillslope.
- **Injection well MAR at lower region of hillslope is recommended.**



Cross-section groundwater level

Conclusions

- The spin-up time required for reaching a steady-state is **longer under dry condition** compared to wet condition.
- This hillslope-valley floor-river valley system required a large amount of water input (precipitation) to establish a reasonable groundwater aquifer. Otherwise, the aquifer is mostly drained out in the hillslope region at equilibrium due to the steep slope.
- Under dry conditions, more than **70% of precipitation is consumed by ET**, whereas under wet conditions, **40% of the water input is transferred to ET and 48% to groundwater recharge**, with the remaining becoming overland flow to river.
- River discharge and river water levels show **seasonal trends under dry conditions** because most of the river water is contributed by baseflow, Under wet conditions, river behavior reflects both **seasonal trends and responses to rainfall events**, due to the significant contribution of overland flow.
- **Pumping wells are not recommended at the hillslope** due to inefficient extraction and a thin aquifer. It is more effective and sustainable to install them in the river valley or valley floor.
- **Injection well MAR is recommended at the lower region of the hillslope** due to fast groundwater transport velocity and a high hydraulic gradient.
- **Challenges:**
 1. MAR at the upper region of the hillslope (where the aquifer is thin) causes **ponding and overland flow** and the water easily lost to ET.
 2. **Real-time field observation of water content** in UZ is needed to manage water input in dry well MAR.

Future work

- Compare different MAR methods (injection well MAR vs. dry well MAR vs. Surface-Ag MAR)
- MAR at different locations (floor and river valley)
- Sensitivity of slopes, Ks, bedrock shapes to groundwater dynamics
- Complexity of subsurface (unconfined & confined aquifer; subsidence.....)