Supplement of

Unveiling the role of groundwater in hydrology and nitrate-N transport over agricultural watersheds in the U.S. Corn Belt: insights from model structure intercomparison

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Text S1. The controlling equation calculating groundwater head for all three groundwater modules varied. Here, we present the governing equations for groundwater head calculations :

For default SWAT+:

$$h_{wtbl,t} = h_{wtbl,\,t-1} * exp[-\alpha_{gw} * \Delta t] + \frac{W_{rchrg}*(1-exp[-\alpha_{gw}*\Delta t])}{800*\mu*\alpha_{gw}} \tag{S1}$$

where $h_{wtbl,t}$ and $h_{wtbl,\,t-1}$ denote the water table height on days t and t−1, respectively (m); α_{gw} is the baseflow recession constant; Δt is the time step (1 day); W_{rchrg} represents the recharge entering the aquifer on day i; and μ is the specific yield of the shallow aquifer.

For SWAT+*gwflow* and SWAT+MODFLOW+RT3D:

$$\Delta h = (\sum Q_{source} - \sum Q_{sink} \pm \sum Q_{lateral})\,(\frac{\Delta t}{S_y \Delta x \Delta y}) \tag{S2}$$

where $\sum Q_{source}$, $\sum Q_{sink}$, and $\sum Q_{lateral}$ represent fluxes from external inputs, losses, and exchanges with neighboring cells, respectively; S_y refers to specific yield (m^3 water / m^3 of bulk material), Δx and Δy denote the cell dimensions of the control volume; Δt is the timestep (daily in this study).

Text S2. The controlling equation calculating groundwater nitrate-N concentration for all three groundwater modules varied. Here we listed all the governing equations for groundwater nitrate-N calculation:

For default SWAT+, nitrate is represented in terms of storage (mass) in the shallow aquifer, which is calculated as:

$$NO3_{sh,\,t} = (NO3_{sh,\,t-1} + NO3_{rchrg,\,t}) * \frac{aq_{sh,t}}{(aq_{sh,t} + Q_{gw} + W_{revap} + W_{rchrg,\,dp})} \tag{S3}$$

where $NO3_{sh,\,t}$ and $NO3_{sh,\,t-1}$ denote the nitrate amount in the shallow aquifer at the end of day t and day t-1, respectively; $NO3_{rchrg,\,t}$ is the nitrate mass entering the aquifer via recharge on day t; $aq_{sh,t}$ is the water storage in the shallow aquifer at the end of day t; Q_{gw} is groundwater flow to the main channel on day t; W_{revap} represents water moving from the aquifer to the soil profile in response to soil water deficits; and $W_{rchrg,\,dp}$ is the recharge to the deep aquifer on day t.

We further calculate the nitrate-N concentration in default SWAT+ follows this equation:

$$conc_t = \frac{NO3_{sh,\,t}}{aq_{sh,t}} \tag{S4}$$

in which $conc_t$ refers to the nitrate concentration at the current time step t.

For SWAT+*gwflow*, nitrate is also represented in terms of storage (mass) in the shallow aquifer following the mass balance:

$$m_t = m_{t-1} + (\sum m_{source} - \sum m_{sink} \pm \sum m_{adv} \pm \sum m_{disp}) * \Delta t \tag{S5}$$

Where m_t and m_{t-1} refer to nitrate amount in the shallow aquifer at the end of day t and day t-1, respectively; $\sum m_{source}$ and $\sum m_{sink}$represent nitrate amount from external inputs and losses, and exchanges with neighboring cells via advection $\sum m_{adv}$ and dispersion $\sum m_{disp}$; Δt is the timestep (daily in this study).

We further calculate the nitrate-N concentration in SWAT+*gwflow* follows this equation:

$$conc_t = \frac{m_t}{v_t} \tag{S6}$$

Where $conc_t$ refers to the nitrate concentration at the current time step t; v_t denotes the current water volume in the corresponding cell.

For SWAT+MODFLOW+RT3D:

$$conc_t = conc_{t-1} - kden * conc_{t-1} * \left(\frac{conc_{t-1}}{kno3 + conc_{t-1}}\right) \tag{S7}$$

in which the nitrate concentration at the current time step ($conc_t$) is calculated as a function of the concentration from the previous time step ($conc_{t-1}$) and a concentration-dependent removal term. The parameter $kden$ denotes the first-order denitrification rate coefficient, which controls the overall magnitude of nitrate reduction. $kno3$ is the half-saturation constant that regulates the sensitivity of the reaction rate to nitrate availability.

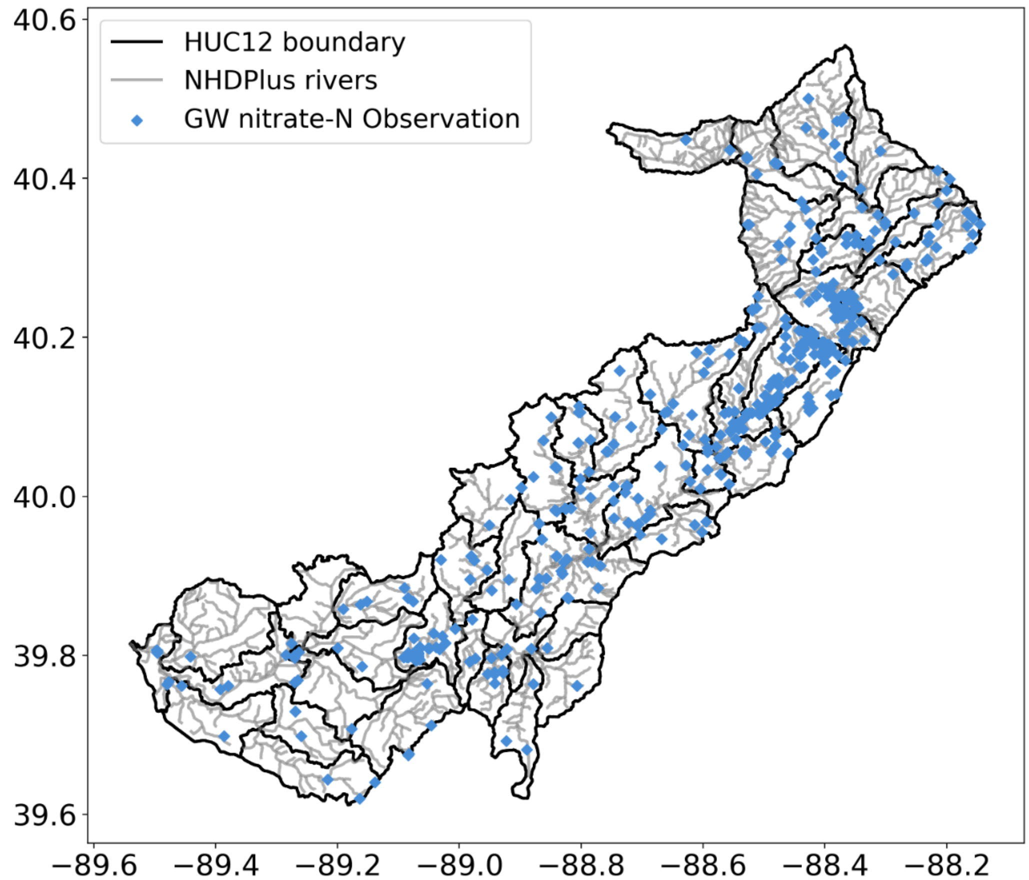

Figure S1. Spatial distribution of groundwater nitrate-N observation sites within the USRB

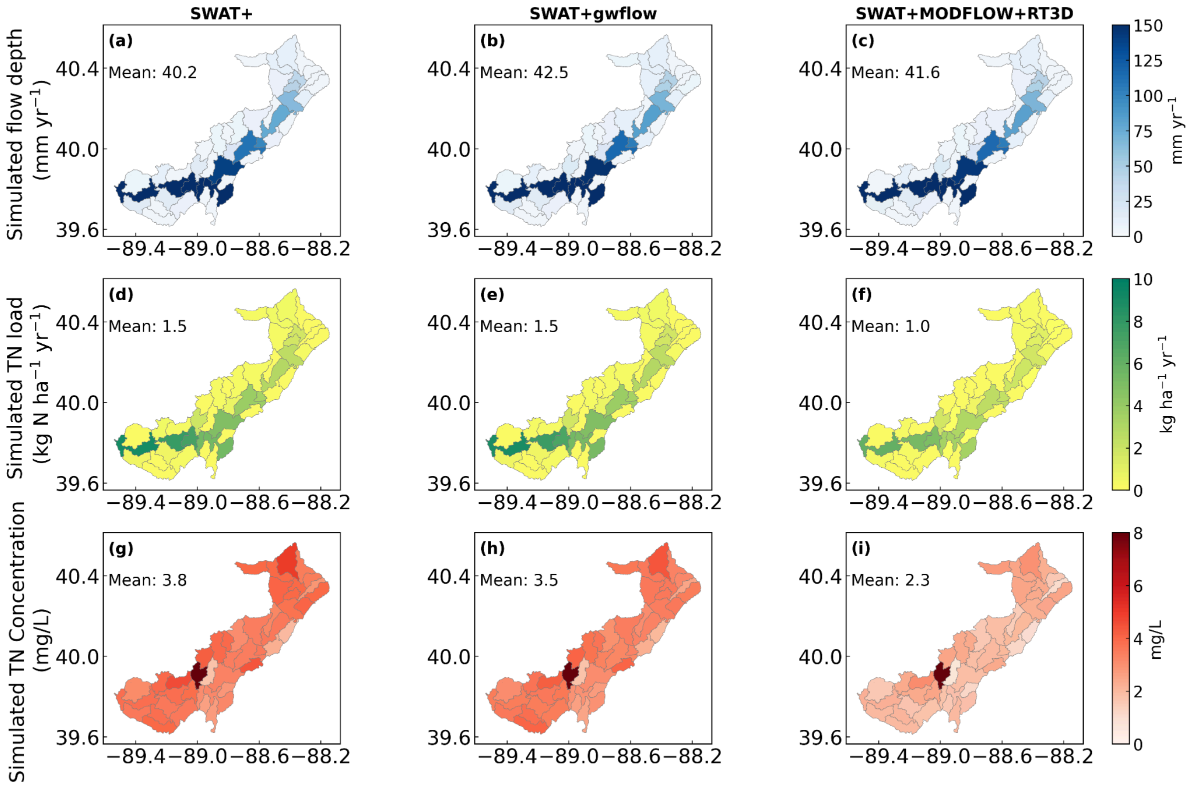

Figure S2. Spatial distribution of simulated flow depth, TN load and TN concentration by default SWAT+ (a-c), SWAT+*gwflow* (d-f), and SWAT+MODFLOW+RT3D (g-i)

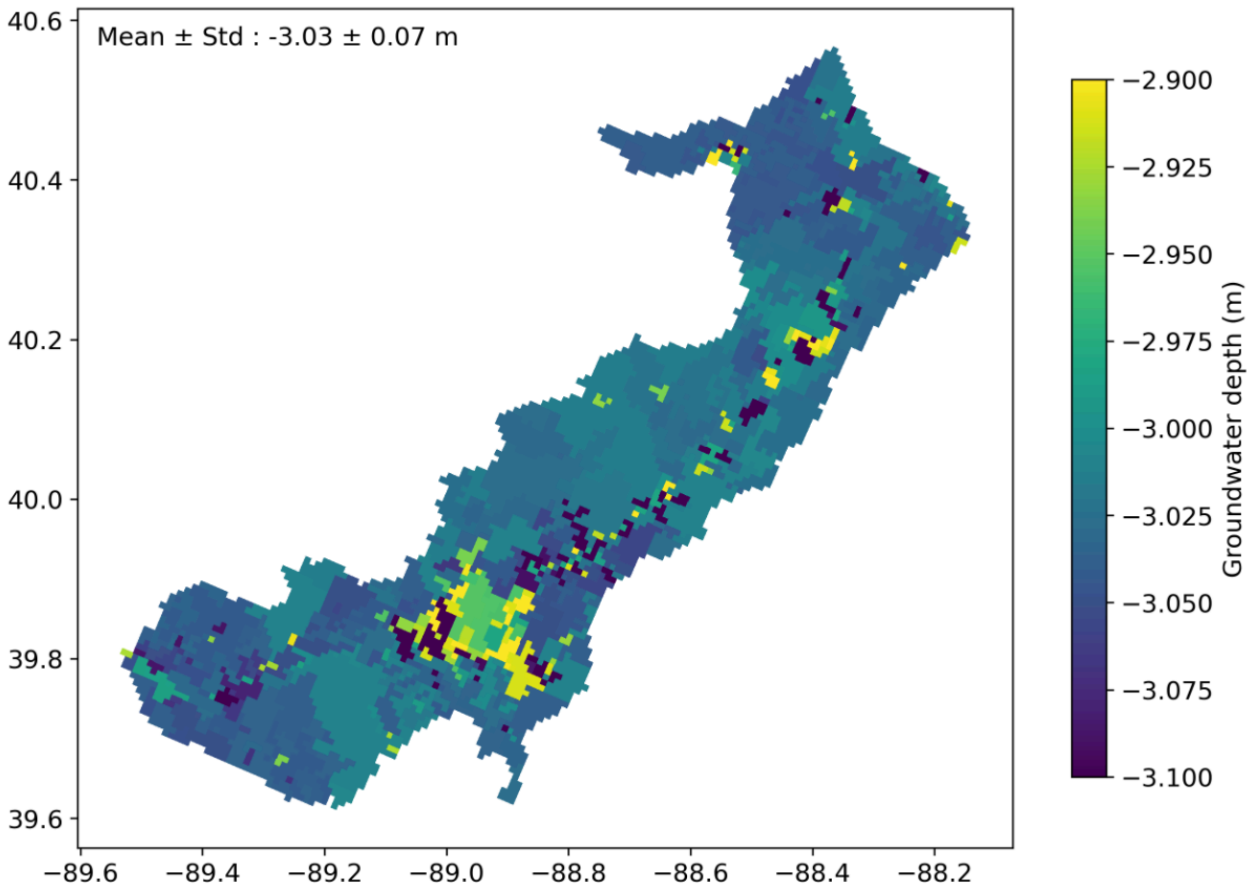

Figure S3. Spatial distribution of simulated groundwater table by default SWAT+ by using a narrow color scale

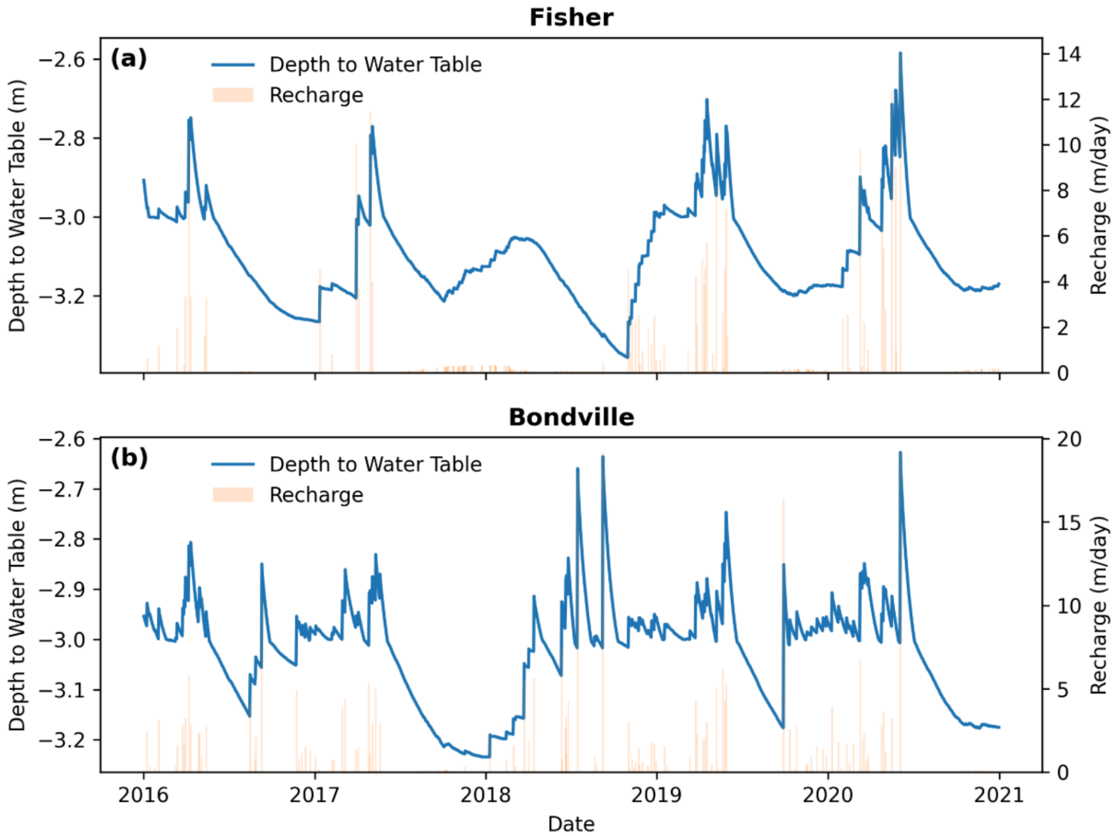

Figure S4. Selected simulated daily groundwater depth (2016-2020) by default SWAT+ at Fisher site (a) and Bondville site (b)

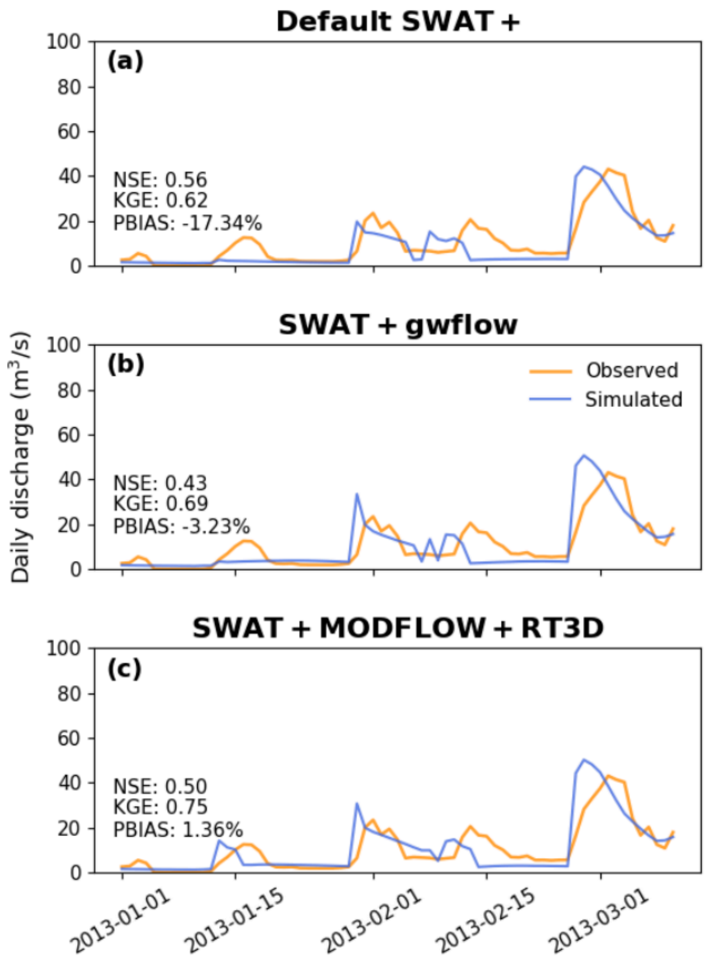

Figure S5. Comparison of simulated and observed streamflow by default SWAT+ (a), SWAT+gwflow (b), and SWAT+MODFLOW+RT3D (c) at the downstream USGS station (05573540) during a selected period (2013.01-2013.03).

Table S1. Estimated annual groundwater recharge in the state of Illinois

Location / Aquifer	Mean annual recharge (mm/year)	Reference
Central Illinois (glacial aquifer system)	~170	Gahala et al., 2024
East-central Illinois (Mahomet Aquifer region, sand & gravel aquifer)	~60	Gahala, 2017
Illinois statewide estimation	~27–107	Illinois Environmental Protection Agency, 2010

Table S2. Estimated groundwater contribution to watershed nitrate-N in the U.S. Midwest

Location/Watershed	Mean annual contribution (%)	Reference
Most midwest sites from USGS	0–50	Norman et al., 2010
Western Lake Erie Basins	~22–77	Song et al., 2022
Otter Creek watershed, Iowa	~50 (during growing season)	Arenas Amado et al., 2017

Table S3. Calibrated parameters across models (Default SWAT+, SWAT+*gwflow*, and SWAT+MODFLOW+RT3D)

Parameter	Value	Unit	Description	Models
epco	0.99	-	Ability of plants to vary water uptake profile from soil	All three models
cn3_swf	0.19	-	Scales field capacity (FC) between input FC and porosity for CN calculation	
perco	0.9	-	Scaling factor for percolation	
tile_lag	96	h	Drain tile lag time	
awc	0.43	mm	Available water capacity of soil layer	
k (soil)	1.33	mm/hr	Saturated hydraulic conductivity for soil	
bd	1.79	g/cm^3	Available water capacity of soil layer	
biomix	0.63	-	Biological mixing efficiency	
nperco	0.12	-	Nitrate percolation coefficient.	
cdn	1.4	-	Denitrification exponential rate coefficient.	
bf_max	1.0	mm	Maximum daily baseflow.	SWAT+ only
alpha	0.05	days	Lag factor for groundwater recession curve.	
revap_co	0.02	-	Re-evaporation coefficient.	

sp_yld	0.05	-	Specific yield for aquifer.	
hlife_n	365	days	Half-life of nitrate in the shallow aquifer.	
Specific yield	0.019	-	Effective porosity controlling groundwater storage release.	SWAT+*gwflow*
Hydraulic conductivity	0.97	m/day	Hydraulic conductivity of the aquifer controlling groundwater flow.	
Streambed depth	5.0	m	Depth of the streambed.	
tile_k	3.5	m/day	Hydraulic conductivity of the tile drain perimeter.	
Denitrification rate	-0.001	day^{-1}	First-order denitrification rate constant for groundwater nitrate.	
Specific Yield	0.033	-	Effective porosity controlling groundwater storage release.	SWAT+MODFLOW +RT3D
Hydraulic conductivity	14.5	m/day	Hydraulic conductivity of the aquifer controlling groundwater flow.	
Streambed depth	5.0	m	Depth of the streambed.	
tile_k	22.0	m/day	Hydraulic conductivity of the tile drain perimeter.	
kden	0.001	day^{-1}	First-order denitrification rate constant for groundwater nitrate.	
kno3	10	mg/L	Half-saturation constant for nitrate in denitrification.	