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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

Yaji Wang[a,b,c], Bin Peng*[a,b,c,d], Mengqi Jia[a], Zewei Ma[a,c], Qianyu Zhao[a], Ryan Bailey[e], Daniel Abrams[f], Jie Yang[a], Kaiyu Guan[a,c,d,h], Ming Pan[g], Yuanxin Song[a,b]

[a] Agroecosystem Sustainability Center, Institute for Sustainability, Energy, and Environment, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA

[b] Department of Crop Sciences, College of Agricultural, Consumer and Environmental Sciences, University of Illinois Urbana-Champaign, Urbana, IL 61801, United States

[c] DOE Center for Advanced Bioenergy and Bioproducts Innovation, University of Illinois Urbana-Champaign, Urbana, IL 61801, United States

[d] National Center for Supercomputing Applications, University of Illinois Urbana-Champaign, Urbana, IL 61801, United States

[e] Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO 80523, United States

[f] Illinois State Water Survey, Urbana, IL 61801, United States

[g] Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92037, USA

[h] Siebel School of Computing and Data Science, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA

* *Correspondence to*: Bin Peng (binpeng@illinois.edu)

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Abstract. Groundwater is an important component in water cycling across agricultural landscapes, but its role in regulating hydrology and nitrogen transport within agricultural watersheds remains highly uncertain, due to limited observations and the reliance on modeling approaches with different model structural representations. Here, we investigated groundwater's role at the watershed scale in the Upper Sangamon River Basin over 2001-2020 by evaluating its annual and seasonal contributions to both hydrology and nitrogen transport using three validated models with different representations of groundwater-related processes, including (1) default SWAT+, (2) SWAT+*gwflow*, and (3) SWAT+MODFLOW+RT3D. These models represent increasing levels of groundwater-process complexity within the same model family, enabling us to isolate the effects of groundwater representation on hydrology and nitrogen transport while minimizing differences arising from other model components. We find that groundwater's annual average net contribution to streamflow ranges from 24.0 % to 31.0 % across models, but its partitioning among contributing pathways varies across models, being dominated by groundwater discharge in the default SWAT+, and by tile flow in SWAT+*gwflow* and SWAT+MODFLOW+RT3D. The multi-year mean net groundwater contribution to nitrate-N export ranges from 16.0 % to 35.0 %. Seasonal analysis shows that groundwater is a year-round source of nitrate–N to the river system, and its contribution peaks after fertilization at more than 10 times that of the non-growing season. Model comparison shows that physically based groundwater models (SWAT+*gwflow* and SWAT+MODFLOW+RT3D) better capture surface-subsurface exchange processes, while the empirical groundwater model of default SWAT+ provides efficient flux estimates. Our results highlight the importance of groundwater representation in shaping watershed hydrologic and nitrogen dynamics and underscore the need to balance process realism with computational efficiency when selecting models for agricultural watershed management.

Keywords: Groundwater; Nitrogen transport; Model structure; SWAT+; SWAT+*gwflow*; SWAT+MODFLOW+RT3D

1 Introduction

Anthropogenic impacts on water quality, primarily driven by agricultural fertilizer and manure applications, have resulted in widespread and increasingly evident degradation of aquatic systems (Bian et al., 2026; Carpenter et al., 2011; Rockström et al., 2009; Van Meter et al., 2016; Zhang et al., 2015). This growing nutrient pollution has raised significant concern within the scientific and management communities, prompting coordinated conservation efforts and policy-driven action to mitigate nutrient pollution over agricultural watersheds (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). Groundwater plays a critical role in agriculture (Kuang et al., 2024) as both a source of irrigation and a transport mechanism for leached solutes. Conceptually, the groundwater system is integrally connected to the soil-plant-atmosphere continuum, receiving net inputs through recharge processes and

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thus operating as a dynamic component rather than an isolated compartment in water and nutrient cycling (Condon et al., 2021). Groundwater is also connected with rivers through dynamic, bidirectional exchanges between aquifers and stream networks, often representing a significant portion of streamflow and in-stream nutrient loads. Consequently, interactions among groundwater, land surface processes, and river systems are essential for accurately understanding how groundwater regulates water and nutrient transport and budgets across spatial and temporal scales over agricultural landscapes.

Extensive research has investigated groundwater interactions with surface components of the agricultural system, recognizing their critical role in regulating coupled hydro-biogeochemical processes across agricultural landscapes. From a hydrological perspective, groundwater remains a significant component in sustaining streamflow in agriculture-dominated basins, and its role in regulating streamflow can become more pronounced under the long-term influences of conservative practices, which affect the partitioning between runoff and infiltration (Ayers et al., 2022; Price, 2011; Zhang and Schilling, 2006). Groundwater can also regulate evapotranspiration and plant water uptake processes across scales, ultimately influencing crop yield. These effects have been demonstrated at the field scale as revealed by in-situ lysimeter measurements and confirmed at the regional scale as validated by both models and satellite observations (Kahlown et al., 2005; Pinke et al., 2020; Deines et al., 2024).

Beyond these evident functional roles, the fluxes and mechanisms governing the underlying interactions between surface and subsurface systems have also been extensively examined, through in situ monitoring, geophysical methods, tracer-aided analysis, and numerical modeling across agricultural landscape under different hydroclimatic conditions (Atwood et al., 2023). In addition to its hydrological functions, groundwater exerts a key control on nutrient transport and transformation across multiple elements (Bailey et al., 2025a; Zhang et al., 2024b; Zhu et al., 2026). Among these nutrients, nitrogen is especially important due to its high mobility in subsurface systems, its dynamic transport and transformation processes, and widespread impacts on water quality (Rivett et al., 2008; Wen et al., 2024). Due to its high solubility, nitrogen is transported through all groundwater-related hydrological processes discussed above, including its critical role in agricultural catchment nitrogen loading and surface-subsurface exchange processes (Wang et al., 2019; Zhang et al., 2024a). Specifically, groundwater mediates nitrate-N leaching and biogeochemical attenuation processes such as denitrification, thereby shaping the spatiotemporal dynamics of watershed nitrogen fluxes, as demonstrated by tracers-based and process-based modeling studies (Bailey et al., 2015; Sha et al., 2025; Wang et al., 2022). Despite substantial advances in understanding groundwater's role in agricultural systems, **a critical gap remains in achieving a system-level (i.e., integrated across hydrological and biogeochemical processes) and quantitative assessment of groundwater's role in regulating hydrology and nitrogen transport within agricultural watersheds, largely limiting our capacity to manage agricultural watersheds for**

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sustainable productivity and improved water quality through reducing non-point nutrient pollution. This gap largely stems from the scarcity of observational data. Field data from local monitoring wells and seep meters are typically spatially sparse and capture only a limited portion of the watershed, making it unrealistic to deploy across the whole watershed scale. In addition, obtaining a system-level observational dataset that encompasses both surface and subsurface hydro-biogeochemical components remains expensive and challenging (Kalbus et al., 2006; Ma et al., 2024).

As a method for characterizing groundwater nutrient processes across a watershed, process-based modeling is a powerful tool for system-level assessment. However, models are subject to important limitations (Abbott et al., 2019; Condon et al., 2021), particularly model structural uncertainties. Numerical models can differ substantially in their representation of hydrological processes due to variations in governing principles, spatial discretization, and numerical solution schemes, which together define their underlying model structures (Beven, 2012; Lees et al., 2021). From the perspective of groundwater process representation and surface–subsurface coupling, such models can be broadly classified into three categories. The first includes models that incorporate simplified groundwater components while primarily targeting other processes, such as HBV (Bergström, 1975), HSPF (Bicknell, 1996) , WRF-Hydro (Gochis et al., 2025), and SWAT+ (Bieger et al., 2017). These models are generally with limited representation of surface-subsurface interactions. The second comprises coupled modeling frameworks that explicitly link surface and subsurface systems to better represent groundwater dynamics, for example GSFLOW-SWMM (Tian et al., 2015), SWAT-MODFLOW (Kim et al., 2008; Bailey et al., 2016), and SWAT+MODFLOW (Bailey et al., 2025b). These frameworks are typically loosely coupled, with the land surface component providing recharge and other groundwater boundary fluxes, and the groundwater model simulating groundwater flow and associated subsurface processes, including groundwater-stream exchange which is provided to the stream routing schemes of the base model. The third category consists of integrated models, such as CATHY (Camporese et al., 2010), PIHM (Qu and Duffy, 2007), HydroGeoSphere (Brunner and Simmons, 2012), CLM-ParFlow (Kuffour et al., 2020), ATS (Coon et al., 2019), and PAWS (Shen and Phanikumar, 2010; Qiu et al., 2023) which simulate surface–subsurface interactions within a unified physical framework. These structural differences influence each model's ability to represent watershed processes and consequently lead to distinct hydrological signatures.

Specifically for agricultural watersheds, a system-level assessment of groundwater's role in water and nutrient transport requires integrating hydrological processes, biogeochemical cycling, and human management practices. These components jointly control water movement, nutrient transformations, and flux across the surface-subsurface continuum. However, representing these coupled processes increases demands for data and computational resources. Consequently, trade-offs among process realism, data

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availability, and computational efficiency play a central role in model selection (Beven, 2012; Lees et al., 2021). The SWAT+ model and its coupled or extended variants have been widely adopted due to their comprehensive representation of key processes, including hydrology, crop growth, nutrient cycling, and management practices (Arnold et al., 2018; Qi et al., 2018). This versatility makes them particularly well suited for simulating water and nitrogen fluxes at the watershed scale (e.g., HUC12 or larger) and for supporting agricultural water management (Baffaut et al., 2015; Liang et al., 2025; Qi et al., 2020; R. Srinivasan et al., 2010). To enhance the representation of groundwater processes and their interactions with surface water, substantial efforts have been made to advance the SWAT+ framework. Notably, recent developments have introduced physically based extensions, including the coupling of SWAT+ with MODFLOW (groundwater storage; flow) and RT3D (solute mass; transport), as well as the implementation of the *gwflow* module, thereby improving the model's capability to represent spatially distributed groundwater storage, head, flow, and groundwater–surface water interactions (Bailey et al., 2016, 2020a, 2020b, 2023; Wei et al., 2019). These enhanced models are now increasingly used for simulating coupled groundwater-surface water processes at the watershed scale (Jafari et al., 2021; Yang et al., 2024; Yimer et al., 2023; Zhang et al., 2026). Within the SWAT+ family, these three groundwater representations (SWAT+, SWAT+*gwflow*, and SWAT+MODFLOW+RT3D) have emerged as the dominant groundwater modeling choices. Generally, models with more complex groundwater representations are generally expected to provide a more physically realistic representation of groundwater processes (Gleeson et al., 2021; Ntona et al., 2022). Despite the availability of the computationally efficient *gwflow* module, integrated SWAT+MODFLOW (and its extension with RT3D for reactive solute transport) continues to be actively developed and applied in studies requiring detailed simulation of groundwater flow and subsurface reactive transport (Fiorese et al., 2025; Lee et al., 2026; Zhang et al., 2026). At the same time, the practical limitations of the default conceptual groundwater routine remain inferred rather than quantitatively demonstrated. The widespread adoption of these three groundwater representations has established a hierarchy of perceived model realism within the SWAT+ family, yet the extent to which differences in model structure influence simulated watershed hydrology and nitrogen transport remains insufficiently understood. In particular, the causal relationships between model structural formulations and their resulting predictions have not been systematically examined.

This study directly addresses these gaps by systematically assessing the role of groundwater in hydrology and nutrient transport over typical agricultural watersheds in the U.S. Corn Belt and quantifying the uncertainty stemming from different model structures. We aim to answer two scientific questions: (1) What is the role of groundwater in regulating hydrology and nitrogen transport within representative agricultural watersheds in the U.S. Corn Belt? (2) How do different subsurface model structures (SWAT+, SWAT+*gwflow*, SWAT+MODFLOW+RT3D) influence the representation of

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hydrology and nutrient transport in agricultural watersheds? The U.S. Corn Belt, a region producing almost one third of global corn and soybean production, is characterized by relatively shallow groundwater table depths (Illinois Department of Agriculture, 2023; Shapiro and Falcone, 2022), which facilitate active groundwater–surface water interactions. Notably, ~40% of rainfed maize area in the Corn Belt is found to be influenced by groundwater (Deines et al., 2024). Intensive agricultural management also leads to extensive nutrient pollution in the U.S. Corn Belt (Oates et al., 2025) and all Midwestern states have developed nutrient loss reduction strategies for controlling non-point source nutrient pollution (NLRS Scenario Development, 2026; Srinivas et al., 2020). Therefore, having a comprehensive understanding of groundwater's role in such systems, along with selecting appropriate modeling tools, is of critical importance for improving water and nutrient management in the U.S. Midwestern agricultural watersheds. This is particularly important when evaluating bioenergy and perennial land-use scenarios, where differences in the representation of groundwater processes may lead to substantially different predictions of water quantity and nutrient export.

2 Materials and Methods

2.1 study area

We conducted research at the Upper Sangamon River Basin (USRB), a Hydrologic Unit Code (HUC) 8 level watershed (07130006) located in central Illinois, USA (Fig. 1a). The watershed is dominated by agricultural land use, primarily consisting of corn–soybean rotations, which cover approximately 80.0% of the total watershed area. The region has a humid continental climate, characterized by warm summers and cold winters, with an average annual precipitation of approximately 1000 mm (Niroula et al., 2023). The dominant soil types are Mollisols, which are generally productive but often exhibit poor natural drainage conditions (Rhoads et al., 2024). The legacy of Quaternary glaciation has resulted in relatively flat topography and poorly drained soils across much of the region. As a result, subsurface tile drainage systems have been widely installed to improve soil drainage and agricultural productivity.

The USRB is largely underlain by the Mahomet Aquifer, one of the most important aquifers in central Illinois. This aquifer represents a typical sand and gravel aquifer, composed of coarse-grained unconsolidated materials that overlie bedrock and were primarily formed by Quaternary glacial activities and fluvial outwash deposits (Abrams et al., 2023). Such hydrogeologic conditions suggest potentially active surface water–groundwater interactions within the region. Moreover, aquifers that occur close to the land surface are generally more vulnerable to contamination from surface-derived pollutants, such as agricultural fertilizers and point-source discharges.

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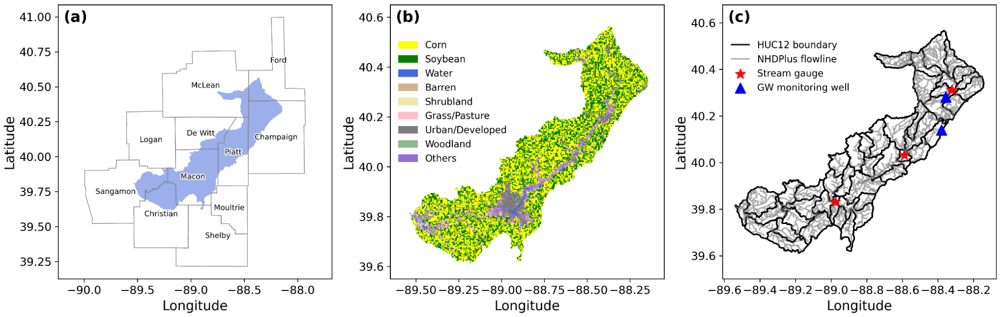

Figure 1. Location (a), land use (b), and watershed hydrologic features (c) of the Upper Sangamon River Watershed (HUC 07130006) in central Illinois, USA.

2.2 Numerical models

2.2.1 Default SWAT+

SWAT+ (Bieger et al., 2017) is the next-generation version of the widely used Soil and Water Assessment Tool (SWAT). It has been extensively applied in watershed-scale water resource management across diverse landscapes due to its comprehensive representation of hydrological and biogeochemical processes. The model simulates the transport and allocation of water and nutrients from land surfaces to river systems, while also incorporating a wide range of management practices and representing the full growth cycles of various plant species. Groundwater processes are also represented in SWAT+. These processes are simulated using a conceptual, empirical formulation, specifically based on a linear reservoir approach (see Equation S1 in the Supplementary Material). Nitrogen dynamics in groundwater, represented as nitrate-N, are modeled under a well-mixed assumption, whereby nitrate-N concentrations are assumed to be uniformly distributed within the aquifer storage (Equation S2). The interactions between the river and groundwater systems are also simplified in the default SWAT+ model. While groundwater contributions to streamflow are represented, river seepage (i.e., transmission losses) is not routed to the shallow aquifer. Instead, these losses are implicitly assigned to other storage components that are not explicitly included in the dominant water cycle (Fig. 2a).

2.2.2 SWAT+*gwflow*

SWAT+*gwflow* is an enhanced version of SWAT+ that improves the representation of groundwater hydrology and associated nutrient transport processes (Bailey et al., 2020a; Tuladhar et al., 2025). The *gwflow* module is called as a subroutine within the SWAT+ code during each daily time step, replacing the default groundwater module. In this framework, the unconfined aquifer is represented using a physically based approach, discretized into a two-dimensional grid of cells to capture spatial heterogeneity at a finer resolution. Inflows and outflows represented in the module include recharge (from soil deep percolation for HRUs (hydrological response unit) connected spatially to the cells),

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groundwater-channel exchange (for cells connected spatially to channels; Fig. 2b), groundwater-lake exchange, pumping, tile drainage outflow, and lateral flow between cells. Lateral flow between cells is calculated using Darcy's Law. For channel-connected cells, water exchange between the river and aquifer is calculated using Darcy's law, driven by the hydraulic gradient between river stage and groundwater head. Cells designated as containing tile drains will yield water to a receiving channel if the water table rises above a specified tile drain depth.

The module is based on an explicit control volume approach, in which groundwater storage in each grid cell is updated at each daily time step using the balance of inflows and outflows. Required hydrogeologic properties for each cell include ground surface elevation (m), aquifer thickness (m; ground surface to bedrock), initial groundwater head (m), hydraulic conductivity (m/day), and specific yield.

Nutrient transport within the groundwater system (currently including nitrate-N and phosphorus) is simulated within the *gwflow* module using the advection–dispersion–reaction equation, accounting for the movement and transformation of solutes within the aquifer (Tuladhar et al., 2025) (Equation S5). Mass of nitrate-N and phosphorus is transported with the listed groundwater inflows and outflows, with the mass (g) within each grid cell updated each daily time step. Nutrient concentration is then calculated by dividing the new mass (g) by the new groundwater storage (m^3). In addition to mass inputs and outputs, nitrate-N mass can decrease due to denitrification.

2.2.3 SWAT+MODFLOW+RT3D

The SWAT+MODFLOW+RT3D model (Bailey et al., 2025b) couples three models: SWAT+ serves as the primary model to simulate land surface processes and river routing; MODFLOW is used to simulate groundwater heads and surface–subsurface exchange processes, with percolation from the soil profile specified as the upper boundary flux and groundwater-river exchange provided to SWAT+ for channel routing; and RT3D is applied to simulate nitrate-N transport within the groundwater system. The overall model structure is conceptually similar to that of SWAT+*gwflow* in terms of representation and underlying principles. However, MODFLOW enables a fully three-dimensional representation of the aquifer (Fig. 2c), allowing for multiple layers. Owing to the more complex numerical schemes and the coupling of multiple models, the computational cost of the SWAT+–MODFLOW–RT3D is substantially higher than that of the default SWAT+ and SWAT+*gwflow*, particularly when simulating multilayer aquifers.

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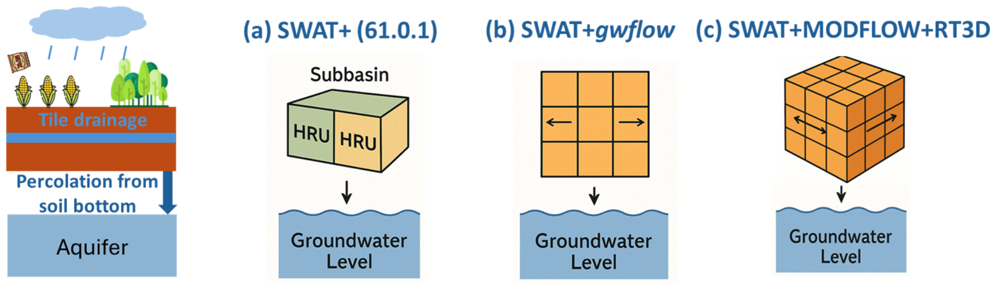

(d) **Discretization**	Lumped (HRU scale)	2D grid	3D grid
First principle of hydrology	Mass balance	Darcy's law	Dracy's law
First principle of reactive transport	Mass balance	Advection-dispersion-reaction equation	Advection-dispersion-reaction equation
Calculation method	Explicit solution	Explicit solution	Implicit solution
Interaction with river	Unidirectional exchange	Bidirectional exchange	Bidirectional exchange

Figure 2. Conceptual comparison of groundwater representations in SWAT+ (a), SWAT+*gwflow* (b), and SWAT+MODFLOW+RT3D (c), along with a summary of key structural and process differences among the three modeling frameworks (d).

2.3 Model Setup, Calibration, and Validation

2.3.1 Setup Strategy

To ensure a consistent and comparable modeling framework across the three models, simulations were conducted over the period 1986–2020. The first 15 years were used as a warm-up period to minimize the influence of initial conditions, particularly for the aquifer dynamics. The remaining 20 years (2001–2020) were divided into a 7-year calibration period (2001–2007) and a 13-year validation period (2008–2020), considering the temporal distribution and availability of observational data.

We used NHDPlus V2 to configure the watershed, including watershed boundaries, catchment geospatial data for delineation, and flowlines to establish the hydrological topology. HRUs were defined using the dominant HRU method, based on the combination of land use (CDL), soil (SSURGO), and slope (DEM 30 m resolution) at catchment scale (Table 1). Daily meteorological data was used to drive the hydrological simulations. Nitrogen inputs within the watershed were also considered, including fertilizer application, point source pollution, and atmospheric deposition, all represented at an annual resolution (Yang et al., 2026). Tile drainage was configured based on locally derived empirical parameters, with a prescribed drain depth of 1.04 m (Wallington and Cai, 2023). A representative corn–soybean rotation commonly practiced in Illinois was implemented in the model. Planting and harvest dates were specified according to typical crop management practices in the region (University of

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Illinois Extension, 2023). All three models rely on the default SWAT+ framework for land-phase process simulation, ensuring consistent representation of terrestrial processes.

To ensure a fair comparison among the three models, the initial groundwater depth was uniformly set to 3 m at the start of the model warming-up period (year 1986), based on the local average groundwater level (McKenna et al., 1989). The upper boundary condition is uniformly defined as recharge input to the aquifer. In contrast to the consistent upper boundary condition, the lower boundary differs substantially among the three models. In the default SWAT+, groundwater loss is represented as seepage to a deep aquifer, effectively acting as a conceptual sink. In SWAT+*gwflow*, the aquifer is represented as a single-layer system with a no-flow lower boundary (bedrock) due to structural limitations. In SWAT+MODFLOW+RT3D, the subsurface can be discretized into two layers, allowing vertical exchange between an unconfined aquifer and an underlying confined aquifer. The default SWAT+ was configured at the HRU level, i.e., catchment scale here, to best demonstrate its capability in representing groundwater processes. In SWAT+*gwflow*, the aquifer was discretized into a regular grid with a spatial resolution of 200 m. For the MODFLOW setup, the aquifer was delineated following the same discretization strategy as in SWAT+*gwflow*. Aquifer properties were derived from datasets provided by the Illinois State Water Survey (Daniel et al., 2023), while aquifer thickness (defined as the vertical distance from the land surface to bedrock) was obtained from the 30 m BDTICM (Absolute depth to bedrock) dataset (Hengl et al., 2017). Both SWAT+*gwflow* and SWAT+MODFLOW incorporate additional aquifer flux modules. In SWAT+*gwflow*, these include saturation excess flow, for conditions of the water table intersecting the ground surface, and tile drainage processes, whereas in SWAT-MODFLOW, tile drainage is simulated using the DRN (Drain) package.

2.3.2 Model calibration and validation

All three models were calibrated to ensure reliable simulation performance and to evaluate their capability in representing hydrological and nitrogen transport processes. Model calibration was conducted sequentially. Stream discharge and groundwater recharge were first used to constrain watershed-scale water balance and recharge partitioning. Groundwater hydraulic parameters were then adjusted using groundwater head observations to improve the representation of subsurface flow dynamics. Finally, nitrogen-related parameters were refined using observed TN loads (here defined as the sum of nitrate-N and nitrite-N), observed groundwater nitrate-N concentrations, and estimates of groundwater contributions to nitrate-N export, thereby constraining both watershed nitrogen export and the relative role of groundwater in nitrate-N transport. The calibration employed five primary sources of information: observed stream discharge, groundwater head observations, watershed TN loads, groundwater nitrate-N concentration observations, and independent estimates of groundwater recharge and groundwater contributions to nitrate-N export. Observed stream discharge, groundwater head, and TN load data were

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treated as hard constraints during model calibration. In contrast, independent estimates of groundwater recharge and groundwater contributions to nitrate-N export were used as soft constraints. Groundwater nitrate-N concentration observations were also treated as a soft constraint, as temporally continuous records were unavailable for most monitoring wells and were therefore used primarily to evaluate whether simulated concentrations fell within the observed range (Fig. S1).

The calibration procedure was implemented using the *pymoo* Python package, which applies evolutionary optimization algorithms for parameter estimation. Observational datasets for hard calibration were obtained from the U.S. Geological Survey (USGS), and the locations of discharge, TN load and groundwater monitoring sites are shown in Fig. 1(c). The estimated recharge and groundwater contribution to watershed nitrate-N are listed in the supplementary materials (Table S1 and S2). The parameters selected for calibration were identified through reference to previous modeling studies for the same watershed (Table S3).

Model performance was evaluated using three commonly used metrics: the Nash–Sutcliffe efficiency (NSE), the Kling–Gupta efficiency (KGE), and percent bias (PBIAS). NSE and KGE assess the agreement between simulated and observed values, while PBIAS quantifies the overall bias of the simulations relative to observations.

Table 1. The input features for model development and their data sources. Note: Variables are grouped as dynamic (daily meteorological forcings) or static (soil properties, watershed characteristics, and annually updated nitrogen-related variables) for modeling.2.4 Analysis of SW-GW and groundwater mass balance.

Category	Input feature	Source	Reference
Meteorological variables (Daily)	Precipitation (mm)	PRISM Climate Group (4 km)	https://climatedataguide.ucar.edu/climate-data/prism-high-resolution-spatial-climate-data-united-states-maxmin-temp-dewpoint
	Maximum temperature (°C)	PRISM Climate Group (4 km)	
	Minimum temperature (°C)	PRISM Climate Group (4 km)	
	Relative humidity (%)	PRISM Climate Group (4 km)	
	Wind speed ($m\ s^{-1}$)	NOAA (stations)	https://www.ncei.noaa.gov

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	Solar radiation (MJ m^{-2})	Illinois Climate Network (stations)	https://warm.isws.illinois.edu/warm/weather/
Nitrogen cycles (Annual)	Fertilizer application rate (kg N ha^{-1} yr^{-1})	Cropland Data Layer (30 m)	https://croplandcros.scinet.usda.gov/
	Point source pollution (kg N yr^{-1})	ECHO dataset (stations)	https://echo.epa.gov/trends/loading-tool/get-data/custom-search
	Atmospheric N deposition (kg N ha^{-1} yr^{-1})	TREND-nitrogen (County)	https://doi.pangaea.de/10.1594/PANGAEA.917583
Soil properties (Static)	Bulk density (g cm^{-3})	SSURGO	https://www.nrcs.usda.gov/resources/data-and-reports/soil-survey-geographic-database-ssurgo
	Saturated hydraulic conductivity (mm h^{-1})	SSURGO	
	Soil organic carbon (g C kg^{-1})	SSURGO	
	Clay content (g kg^{-1})	SSURGO	
	pH	SSURGO	
Watershed characteristics (Static)	Flowline topology	NHDPlus V2	https://nhdplus.com/NHDPlus/NHDPlusV2_home.php
	Watershed area (km^2)	NHDPlus V2	
	Land use type	Cropland Data Layer (30 m)	https://croplandcros.scinet.usda.gov/
	Aquifer depth (m)	BDTICM (30 m)	https://files.isric.org/soilgrids/former/2017-03-10/data/
	Aquifer hydraulic conductivity (m/day)	Illinois State Water Survey	Abrams et al., 2023
	Aquifer specific yield	Illinois State Water Survey	

2.4 Analysis of surface water-groundwater exchange and groundwater mass balance

We analyzed surface water-groundwater (SW-GW) exchange processes and the groundwater mass balance simulated by SWAT+, SWAT+*gwflow*, and SWAT+MODFLOW+RT3D to diagnose structure differences in groundwater representation across model frameworks. SW-GW interactions were analyzed by quantifying water exchanges among the soil profile, aquifer system, and stream network. Specifically, each groundwater unit receives recharge from the bottom of the soil profile. In addition, aquifer units hydraulically connected to the stream network may receive water from stream seepage. This stream seepage is defined as the surface water to groundwater flux (SW→GW). Conversely, groundwater contributes to surface water through discharge to stream channels driven by hydraulic gradients. This component is quantified as the groundwater to surface water flux (GW→SW).

In addition to groundwater exchange fluxes, changes in groundwater storage and groundwater head were also examined to characterize groundwater dynamics. The groundwater water balance was evaluated by accounting for all inflow and outflow components of the groundwater system and the resulting change in groundwater storage. The equation for groundwater water balance is as follows:

$$Q_{recharge} + Q_{sw-gw} = Q_{gw-sw} + seepage + evap + \Delta storage \qquad (1)$$

Where $Q_{recharge}$ represents the daily recharge from the soil profile to the shallow aquifer, and Q_{sw-gw} denotes the flux from the river system (here referred to as surface water, SW) to the groundwater (GW). These two terms act as sources in the present analysis. Q_{gw-sw} represents the contribution of groundwater to surface water, $seepage$ refers to the percolation from the shallow aquifer to the deep aquifer, while $evap$ denotes groundwater re-evaporation. Finally, $\Delta storage$ represents the change in groundwater storage.

Due to differences in model structure, the representation of Q_{gw-sw} varies across models. In the default SWAT+, the Q_{gw-sw} denotes a single component, namely the groundwater flux to the stream system. In contrast, in SWAT+*gwflow* and SWAT+MODFLOW+RT3D, this flux is explicitly partitioned into multiple components, as described by Equations 2 and 3, respectively:

$$Q_{gw-sw} = Q_{gw\_discharge\_sw} + Q_{tile\_discharge\_sw} + Q_{satx\_discharge\_sw} \qquad (2)$$

$$Q_{gw-sw} = Q_{gw\_discharge\_sw} + Q_{tile\_discharge\_sw} \qquad (3)$$

Where $Q_{gw\_discharge\_sw}$ represents groundwater discharge to the stream driven by the hydraulic gradient between groundwater head and stream stage, $Q_{tile\_discharge\_sw}$ denotes excess water removed via tile drainage, and $Q_{satx\_discharge\_sw}$ refers to water released through saturation-excess flow at the ground surface.

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Given that all three models simulate only nitrate-N (NO_3^--N) as the nitrogen species, the mass balance analysis is conducted specifically for NO_3^-. The formulation follows the same structure as the water balance, with consistent definitions of fluxes and storage terms. The key distinction is the inclusion of an additional sink term, denitrification, which represents the irreversible loss of NO_3^- through biogeochemical processes. The equation can be expressed as follows:

$$N_{recharge} + N_{sw-gw} = N_{gw-sw} + seepage + denit + \Delta storage \quad (4)$$

Where $N_{recharge}$ represents the Nitrate-N from daily recharge from the soil profile to the shallow aquifer, and N_{sw-gw} denotes the Nitrate-N from SW to GW. These two terms act as sources in the present analysis. N_{gw-sw} represents the contribution of groundwater to surface water, $seepage$ refers to the amount of Nitrate-N in percolation from the shallow aquifer to the deep aquifer (only for default SWAT+), while $denit$ denotes denitrification in groundwater. Finally, $\Delta storage$ represents the change in groundwater storage. Within SWAT+*gwflow*, N_{gw-sw} includes loading from the aquifer to the river via the river bed, loading from tile drainage outflow, and loading from saturation excess flows. Within SWAT+MODFLOW+RT3D, this term includes only loading through the river bed and tile drainage outflow.

3 Results

3.1 Comparative assessment of model performance

3.1.1 Discharge

The daily scale comparison in Figure 3 shows the calibration and validation results between model simulated discharge against observed values. All three models provide satisfactory streamflow performance across the watershed. During the validation period, the NSE for daily discharge ranges from 0.65 to 0.72 for all three sites and the KGE varies between 0.71 and 0.86, indicating a generally robust model setup and reliable reproduction of observed flow dynamics. Model performance shows a consistent improvement from upstream to downstream locations (Figure 3). At the most upstream site, NSE ranges from 0.64 to 0.70 and KGE from 0.71 to 0.78. In contrast, at the most downstream site, NSE increases to 0.69 to 0.72, with KGE values consistently greater than 0.85. This improvement likely reflects the larger contributing areas at downstream stations, which integrate hydrological responses, leading to smoother hydrographs and better agreement with observations (Fig. S1). This phenomenon is also clearly reflected in the PBIAS results. At the upstream headwater station, the lowest (most biased) PBIAS was observed in the default SWAT+ model, reaching -22.75% during the validation period. While both SWAT+*gwflow* and SWAT+MODFLOW+RT3D outperformed the default SWAT+ in the uppermost site, their PBIAS values remained between -17.39% and -18.63%. However, performance significantly improved at the two downstream stations, where PBIAS values for all models ranged from -9.44% to 5.25% during validation.

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Notably, incorporating *gwflow* or MODFLOW improves the simulation of baseflow, especially by reducing simulation bias, as illustrated by the representative example in Fig. S5. Overall, the consistently strong performance across multiple gauges suggests that all three models are capable of capturing key hydrological processes and spatial variability within the watershed, providing a reliable basis for further analysis of water dynamics.

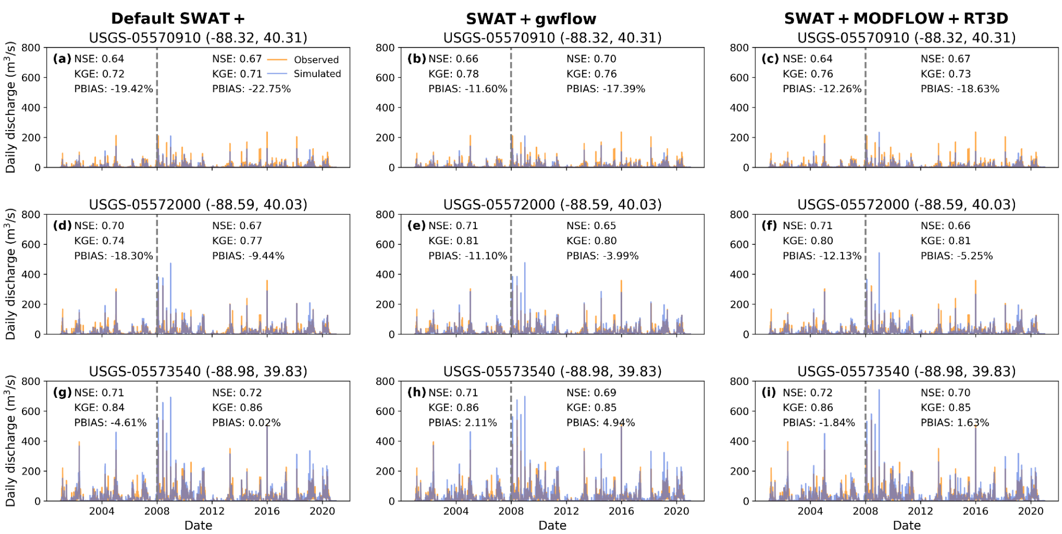

Figure 3. Model performance on daily discharge of default SWAT+ (a, d, g), SWAT+*gwflow* (b, e, h), and SWAT+MODFLOW+RT3D (c, f, i). The grey dashed lines indicate the division of calibration (2001-2007) and validation (2008-2020) period.

3.1.2 TN Load

All three models are able to capture the daily dynamics of total nitrogen (TN) load, although their performance is generally lower than that for streamflow simulation (Fig. 4). At the upstream site (USGS-05570910), all three models show similar performance, with moderate correlation (*r*: 0.76 – 0.81) but relatively low NSE values (0.25 – 0.43) during calibration period, indicating limited ability to reproduce the magnitude of daily TN loads. At the midstream site (USGS-05572000), model performance improves during calibration (NSE: 0.50–0.65; R: 0.89–0.90), suggesting that the models can reasonably capture TN dynamics under fitted conditions. However, validation performance drops (NSE: 0.18–0.39), despite relatively high correlations (*r*: 0.68–0.78). This discrepancy is likely related to the sparse nitrate-N monitoring dataset, which provides limited constraints on the magnitude of daily TN loads, particularly for high-flow or extreme events. As a result, the models are able to capture temporal variability but struggle to reproduce load magnitudes. The downstream site shows the highest NSE during the TN validation period (0.61 - 0.86), likely due to it capturing several peak values in the observation datasets.

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This reduction in performance may result from uncertainties in management practices, particularly the timing of fertilization, which can vary across years, leading to interannual variability in nitrogen loading.

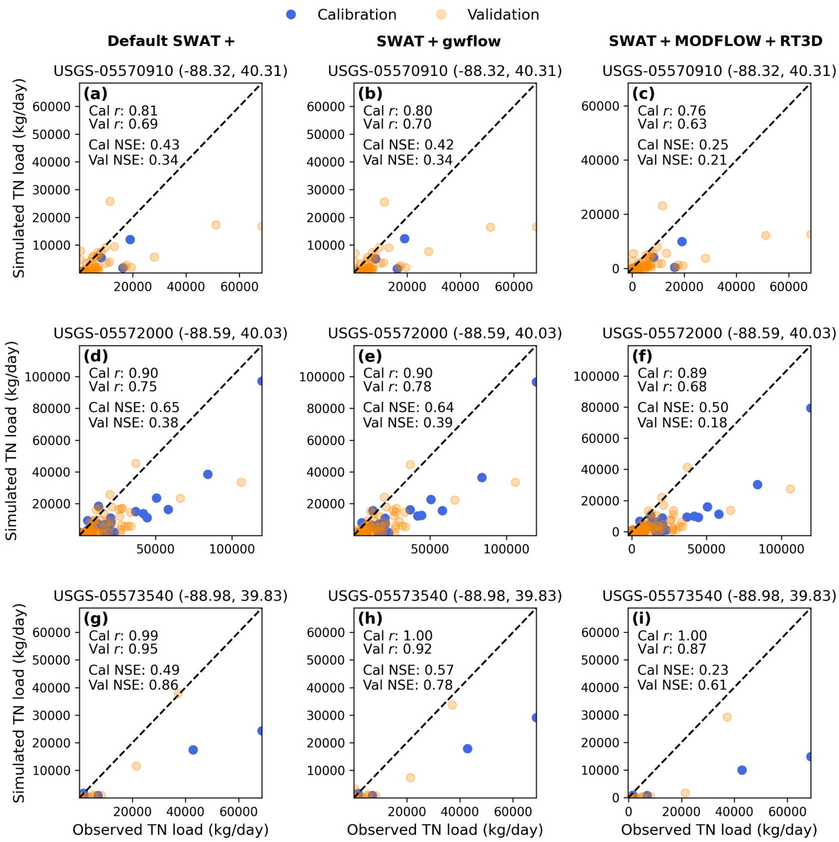

Figure 4. Model performance on TN load of default SWAT+ (a, d, g), SWAT+*gwflow* (b, e, h), and SWAT+MODFLOW+RT3D (c, f, i)

3.1.3 Groundwater head

The simulated groundwater heads from the three models show distinct differences in their ability to reproduce observed dynamics at both observation sites, despite sharing the same initial depth (3 m) and a 15-year warm-up period (Figure 5). At the Fisher site (Fig. 5a), these differences reflect clear contrasts in model structure, with mean absolute error (MAE) ranging from 0.44 to 0.87 m. The default SWAT+ produces an overly smoothed response with limited temporal variability, indicating a reduced capacity to capture short-term groundwater fluctuations, despite yielding the lowest MAE (0.48 m). In contrast, the SWAT+*gwflow* and SWAT+MODFLOW+RT3D better reproduce the observed temporal variability and fluctuation amplitude, although this comes at the expense of slightly higher MAE values (MAE: 0.61 m and 0.87 m).

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At the Bondville site, the three models exhibit notable differences in their representation of groundwater dynamics despite having comparable MAE values ranging from 2.01 to 3.50 m (Fig. 5b). The default SWAT+ again produces a response with limited temporal variability, failing to reproduce observed fluctuations. In contrast, both SWAT+*gwflow* and SWAT+MODFLOW+RT3D capture the general seasonal dynamics within a reasonable range. However, they tend to underestimate the amplitude of groundwater level variations. In addition, SWAT+*gwflow* slightly overestimates the overall groundwater head compared to the observations, whereas SWAT+MODFLOW+RT3D slightly underestimate them. This behavior may also be related to limited site-specific characterization of groundwater properties in the study area, which introduces uncertainty in parameterization and can dampen the simulated variability.

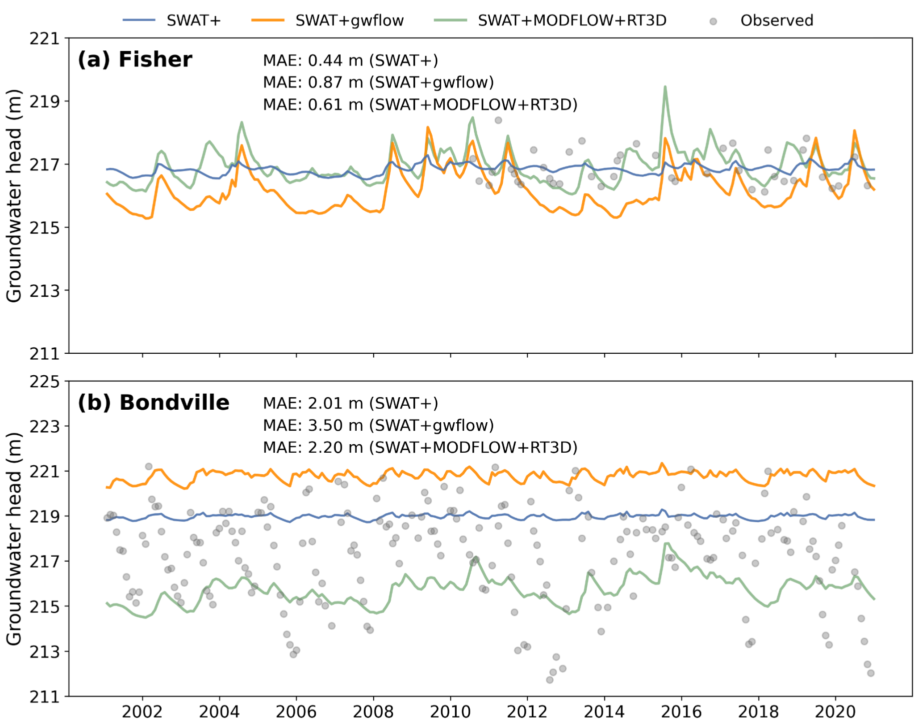

Figure 5. Comparison of monthly simulated and observed groundwater heads across different modeling frameworks at monitoring site Fisher (a) and Bondville (b)

3.1.4 Groundwater nitrate-N concentrations

Simulated groundwater nitrate-N concentrations were compared with observations to evaluate the ability of different model structures in reproducing groundwater nitrate-N dynamics. Groundwater nitrate-N concentrations exhibit distinct distributions among the three models (Fig. 6a). Both the median

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and mean concentrations are lowest in SWAT+ (1.18 mg/L) and higher in SWAT+MODFLOW+RT3D (1.53 mg/L) and SWAT+*gwflow* (1.88 mg/L). In contrast to SWAT, both groundwater-enabled models produce mean concentrations that are broadly consistent with the observations. In terms of across-site performance, SWAT+ yields the lowest mean absolute error (MAE: 1.49 mg/L), whereas SWAT+*gwflow* and SWAT+MODFLOW+RT3D exhibit larger MAE values of 1.78 and 2.44 mg/L, respectively. The simulated groundwater nitrate-N concentrations across all three models fall within a reasonable range, despite their tendency to underestimate the extreme high values observed at a few monitoring sites, discrepancies that may partly stem from monitoring biases. Collectively, these comparisons demonstrate that all three models are able to capture key hydrological and nitrogen dynamics across the watershed, establishing a credible foundation for the mechanistic interpretations presented below.

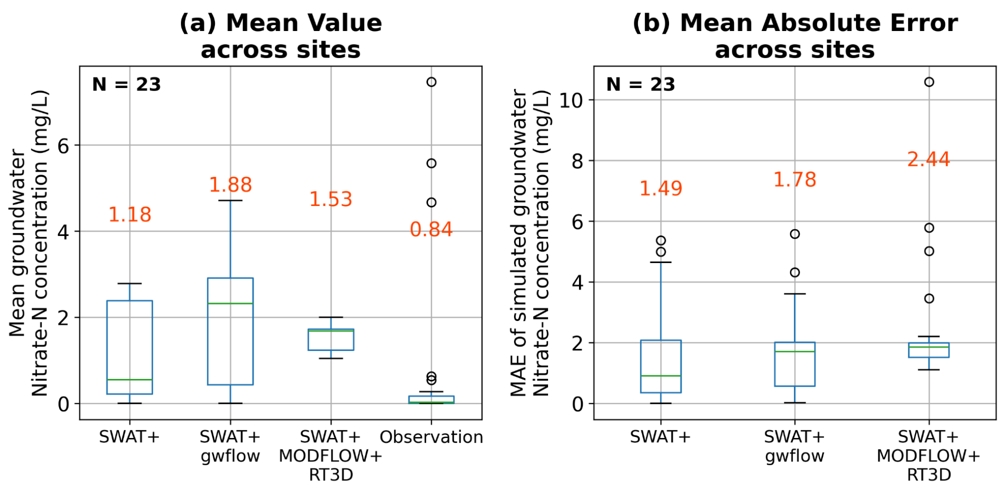

Figure 6. Validation of simulated groundwater nitrate-N concentrations against observations. Panel (a) shows the mean groundwater nitrate-N concentrations (mg L^{-1}) simulated by SWAT+, SWAT+*gwflow*, and SWAT-MODFLOW-RT3D, together with observed values across monitoring sites within the watershed. Panel (b) displays the corresponding mean absolute error (MAE; mg/L) for each model.

3.2 Effects of model structural differences on groundwater hydrology and nitrate-N components

3.2.1 groundwater mass balance

The groundwater water balance was examined to assess structural differences among models in representing subsurface flux components. The mean annual recharge simulated by the three models was 86.2 mm for default SWAT+, 80.8 mm for SWAT+*gwflow*, and 82.1 mm for SWAT+MODFLOW+RT3D (Fig. 7a–c). These values fall within the range of reported recharge estimates for Illinois, as summarized in Table S1. What's more, different from default SWAT+, both SWAT+*gwflow* and

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SWAT+MODFLOW+RT3D explicitly account for surface water contributions to groundwater inflow, representing 8.7% and 7.8% of the total inflow flux, respectively. The different model structures further result in distinct partitioning of groundwater outflow components across the three models (Fig. 7a–c). Based on multi-year mean ratios, groundwater outflow in the default SWAT+ is dominated by discharge to surface water (66.0%) and re-evaporation (24.5%), with a smaller contribution from shallow groundwater seepage to the deep aquifer (4.7%). In contrast, groundwater outflow pathways are represented more explicitly, with tile drainage emerging as the dominant component, accounting for 78.2% and 98.7% of the total outflow in SWAT+*gwflow* and SWAT+MODFLOW+RT3D, respectively. This difference can be further explained by model subsurface structure and does not necessarily indicate that more water is retained in groundwater in SWAT+*gwflow*. Specifically, this is because SWAT+*gwflow* includes an additional outflow component, saturation excess flow, which accounts for 21.6% of the total groundwater outflow.

The groundwater nitrogen balance further highlights structural differences among models in representing subsurface nitrate-N transport processes. For groundwater nitrate-N in-flux, nitrate-N transport is closely tied to its hydrological carrier. As a result, surface water contributions to groundwater are not represented in the default SWAT+, and therefore the corresponding nitrate-N flux is also absent. In contrast, nitrate-N from surface to groundwater accounts for approximately 4.5% of the total groundwater inflow mass in both SWAT+*gwflow* and SWAT+MODFLOW+RT3D. In all three models, denitrification is the dominant groundwater nitrate-N loss pathway, accounting for 77.4%, 67.0%, and 85.4% of total nitrate-N losses in SWAT+, SWAT+gwflow, and SWAT+MODFLOW+RT3D, respectively. Groundwater discharge to surface water represents the second largest loss pathway, contributing 0.95, 1.89, and 1.49 kg N ha^{-1} yr^{-1} (21.2%, 33.0%, and 14.6% of total losses), respectively. In addition, tile drainage serves as an important pathway for groundwater-derived nitrate export in the two coupled models, with fluxes of 1.60 and 1.32 kg N ha^{-1} yr^{-1}, respectively.

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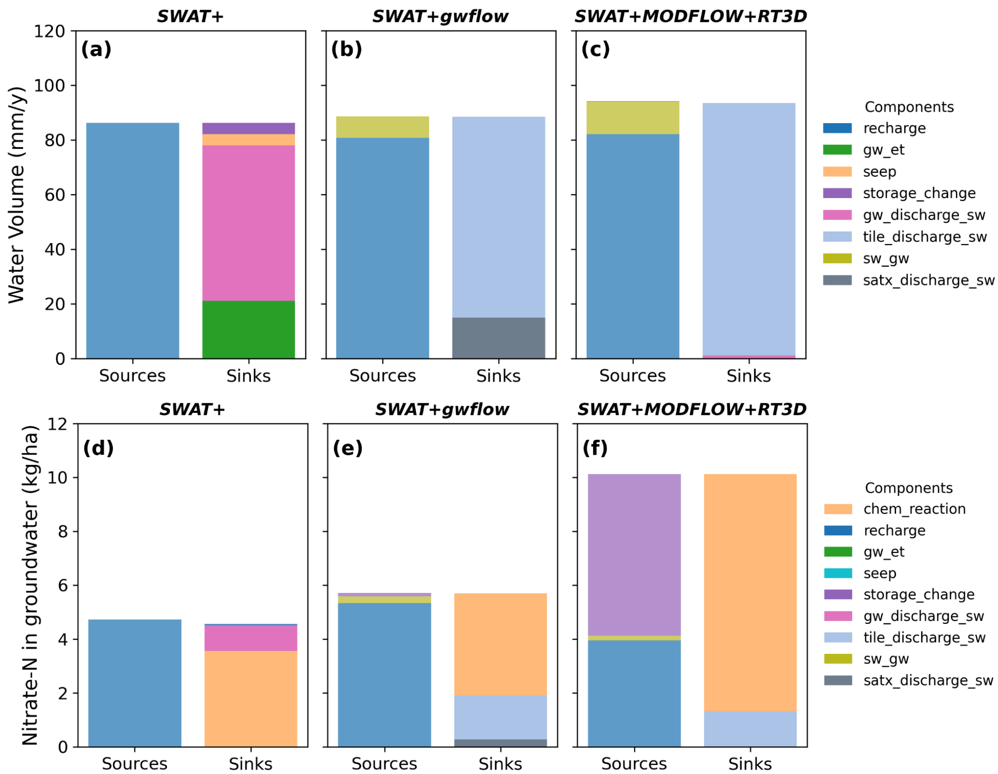

Figure 7. Groundwater balance components for water (a–b) and nitrate-N (c–d). *Recharge* represents the water or nitrate-N flux entering the aquifer from the bottom of the vadose zone; *gw_et* denotes groundwater loss through evapotranspiration; *seep* represents the flux leaving the aquifer through its lower boundary; *storage_change* indicates the change in groundwater storage (water or nitrate-N mass); *gw_discharge_sw* denotes groundwater discharge to surface water driven by hydraulic gradients; *tile_discharge_sw* represents groundwater discharge to surface water via tile drainage; *satx_discharge_sw* represents groundwater discharge to surface water via saturation-excess flow; *chem_reaction* denotes denitrification; ; and *sw_gw* denotes the flux from surface water to groundwater.

3.2.2 Spatial pattern of groundwater head and concentration

Simulated water table depth (m) exhibits substantial differences across modeling frameworks (Fig. 8). The default SWAT+ produces a relatively uniform spatial pattern with a mean depth of −3.03 m. However, this does not indicate a lack of spatial variability, but rather a relatively small range of variation across the domain (Fig. S2). In contrast, SWAT+*gwflow* shows increased spatial variability and generally deeper groundwater levels (−2.81 m). The SWAT+MODFLOW+RT3D simulation further enhances

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spatial heterogeneity, with pronounced shallow groundwater zones, particularly in urban areas where permeability information is unavailable, and a higher mean groundwater level (-2.44 m). The lower groundwater levels simulated by SWAT+*gwflow* as compared to SWAT+MODFLOW+RT3D likely are due to saturation excess flow being simulated in SWAT+*gwflow*, which removes groundwater from the aquifer in tables with shallow water tables.

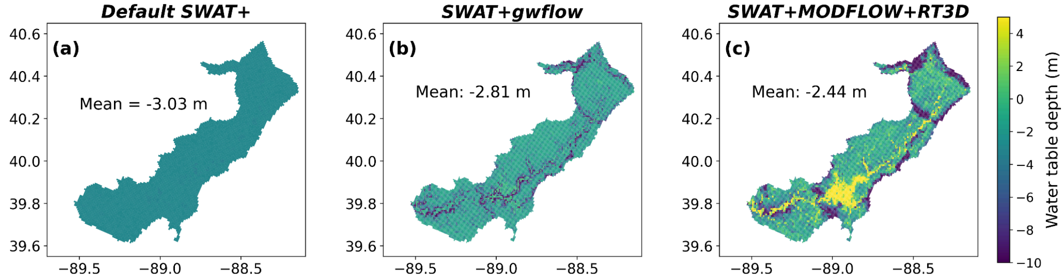

Figure 8. Spatial patterns of annual mean simulated groundwater depth by default SWAT+ (a), SWAT+*gwflow* (b), and SWAT+MODFLOW+RT3D (c)

Simulated nitrate-N concentrations in the shallow aquifer show pronounced differences across modeling frameworks (Fig. 9). The default SWAT+ produces moderate concentrations with a mean of 1.51 mg/L and a relatively heterogeneous spatial distribution. In contrast, SWAT+MODFLOW+RT3D yields substantially lower concentrations (mean = 1.46 mg/L), with most areas exhibiting uniformly low values and limited spatial variability. The SWAT+*gwflow* simulation results in higher overall concentrations (mean = 1.99 mg/L) and stronger spatial gradients, with elevated nitrate-N levels distributed more extensively across the watershed. Although the magnitude and spatial variability differ among models, the overall distribution of high- and low-concentration areas is generally consistent, reflecting the influence of calibration to a common set of observational constraints. The relative consistent spatial pattern simulated by SWAT+MODFLOW+RT3D (Fig. 9c) reflected the combined influence of the soft constraints and calibrated denitrification parameters (e.g., denitrification rate and nitrate-N half-saturation constant), rather than from inherent limitations in representing spatial heterogeneity (Equation S7).

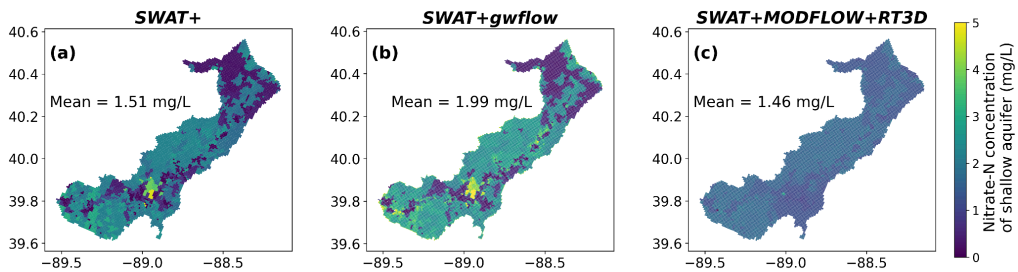

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Figure 9. Spatial pattern of annual mean simulated groundwater Nitrate-N concentration by default SWAT+ (a), SWAT+*gwflow* (b), and SWAT+MODFLOW+RT3D (c)

3.3 Effects of model structural differences on surface water-groundwater interactions

Figure 10 a-c shows the interannual variability of groundwater–surface water exchange fluxes simulated by the three models. The mean annual GW to SW fluxes are on the order of ~19.0–99.9 mm yr^{-1} for the default SWAT+, ~51.7-135.2 mm yr^{-1} for SWAT+*gwflow*, and ~67.1–133.0 mm yr^{-1} for SWAT+MODFLOW+RT3D. In contrast, SW-to-GW fluxes are absent in the default SWAT+, whereas SWAT+*gwflow* and SWAT+MODFLOW–RT3D produce comparable magnitudes of SW-GW exchange, ranging from 3.0–12.1 and 7.4–16.6 mm yr^{-1}, respectively. Both SWAT+*gwflow* and SWAT+MODFLOW+RT3D exhibit a clear increasing trend in SW to GW fluxes over the simulation period. This trend can be attributed to declining groundwater storage, which enhances hydraulic gradients favoring stream leakage, as well as differences in river–aquifer interaction parameterization across models. Despite these differences in magnitude, the interannual dynamics of GW-SW fluxes are consistent across models. All simulations show relatively low values around 2001 and 2012, and the highest value in 2010. These variations are closely linked to climatic conditions, particularly drought-induced reductions in recharge, which directly limit groundwater contributions to streamflow. The net groundwater–surface water exchange is further illustrated in Fig. 11 (a–c). Across all three models, the net GW-SW contribution remains positive, with multi-year mean values ranging from 56.9 to 81.6 mm yr^{-1}. This indicates that groundwater consistently acts as a net source to the stream system and plays a non-negligible role in the watershed's hydrology.

Nitrate-N exchange between groundwater and surface water also exhibits clear interannual variability (Fig. 10 d-f). Similar to water fluxes, the contribution of groundwater to surface water varies across years but follows a consistent temporal pattern among the models. The magnitude of GW-SW nitrate-N fluxes is generally comparable among the three models, with multi-year mean values of 1.13, 1.90, and 1.66 kg N ha^{-1} yr^{-1}, respectively. The remaining differences are primarily attributed to model-specific reactive transport parameterizations, particularly denitrification, which controls nitrate-N removal and ultimately regulates groundwater nitrate-N concentrations (Fig. 7). Consistent with the hydrological results, the default SWAT+ lacks SW to GW nitrate-N flux. Unlike water fluxes, SW to GW nitrate-N fluxes exhibit clear seasonal variability rather than a monotonic increasing trend (Fig. 10 e-f). This behavior likely reflects seasonal variations in nitrate-N availability in surface water, driven by fertilizer application, plant uptake, and runoff processes, which together control the timing and magnitude of nitrate-N transport into the aquifer. Despite the occurrence of nitrate-N transport from surface water to groundwater, when accounting for bidirectional exchanges between groundwater and surface water, the net nitrate-N flux remains positive, indicating a net transfer of nitrate-N from groundwater to streams. In

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SWAT+*gwflow* and SWAT+MODFLOW–RT3D, the net fluxes are 1.66 and 1.17 kg ha⁻¹ yr⁻¹, respectively. These results indicate that groundwater remains a net source of nitrate-N to the stream system despite the presence of reverse nitrate-N transport from surface water to groundwater, highlighting the importance of representing bidirectional groundwater–surface water exchanges when quantifying watershed nitrogen dynamics.

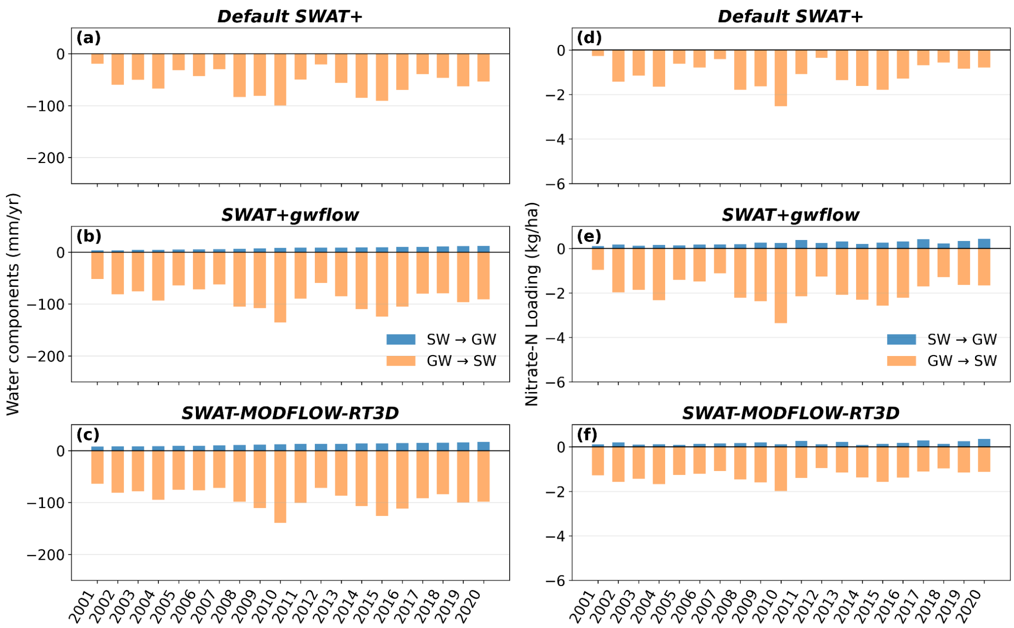

Figure 10. Annual exchange of surface-groundwater on water fluxes (a)-(c) and nitrate-N fluxes (d) - (f) across model structures

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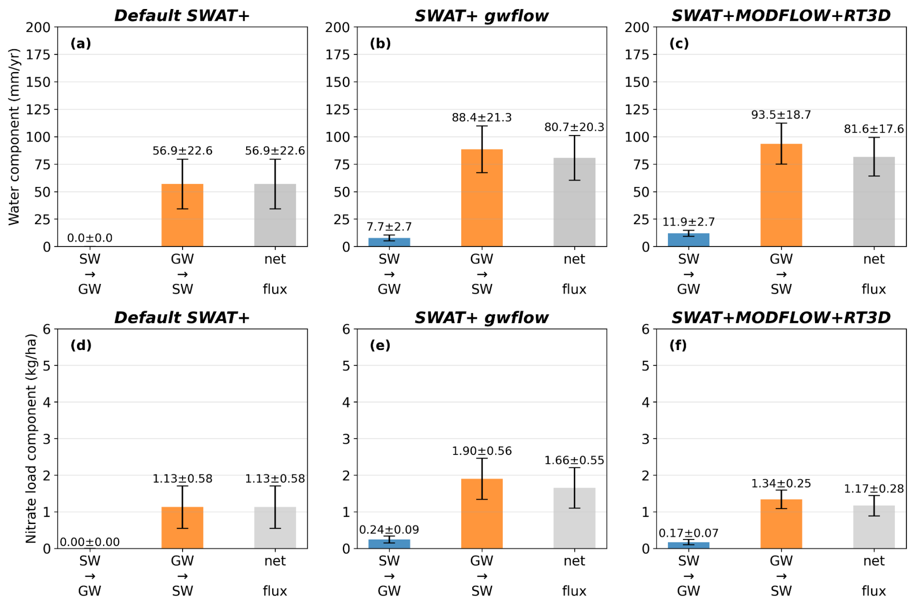

Figure 11. Groundwater–surface water exchange of water (a)-(c) and nitrate-N (d)-(f) across SWAT+, SWAT+*gwflow*, and SWAT-MODFLOW-RT3D

3.4 Effects of model structural differences on groundwater contributions to watershed hydrology and nitrate-N export

The annual dynamics of groundwater contributions to watershed hydrology, accounting for both inflow and outflow components, show consistent temporal patterns across models, with differences in magnitude (Fig. 12 a-b). Groundwater contributes substantially to watershed discharge, with mean contribution ratios of 0.24 ± 0.09 for the default SWAT+, and higher values for both SWAT+*gwflow* (0.34 ± 0.12) and SWAT+MODFLOW+RT3D (0.36 ± 0.12) (Fig. 12a). Similar patterns were observed for net groundwater contributions, although with a slightly reduced ratio (Fig. 12c). All models exhibit pronounced interannual variability, with peak contributions occurring around 2012, corresponding to a drought period. Groundwater contributions to watershed nitrate-N are comparable in magnitude to their contributions to discharge. The default SWAT+ shows the lowest mean contribution (0.16 ± 0.11), whereas SWAT+*gwflow* (0.25 ± 0.15) and SWAT+MODFLOW+RT3D (0.35 ± 0.18) yield higher values. The higher groundwater contribution ratios in the coupled models occur despite constrained by comparable groundwater nitrate-N contribution magnitudes, suggesting that differences in groundwater flow and nitrate-N transport representations may influence the partitioning of groundwater contributions among the models. Net nitrate-N contributions show a similar ranking, increasing from 0.16 ± 0.11 in the default SWAT+ to 0.22 ± 0.13 in SWAT+*gwflow* and 0.33 ± 0.17 in SWAT+MODFLOW+RT3D. Slightly lower net than gross groundwater contributions indicate episodic nitrate-N transport from surface water to

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groundwater (Fig. 12f). All three models exhibit a pronounced peak in 2012, mirroring the hydrologic response to the severe drought. During that year, reduced watershed TN loading increased the relative contribution of surface water-to-groundwater nitrate-N transport to nearly 20% (Fig. 4). This phenomenon demonstrates how extreme hydroclimatic events can temporarily shift the balance of watershed bidirectional exchange processes.

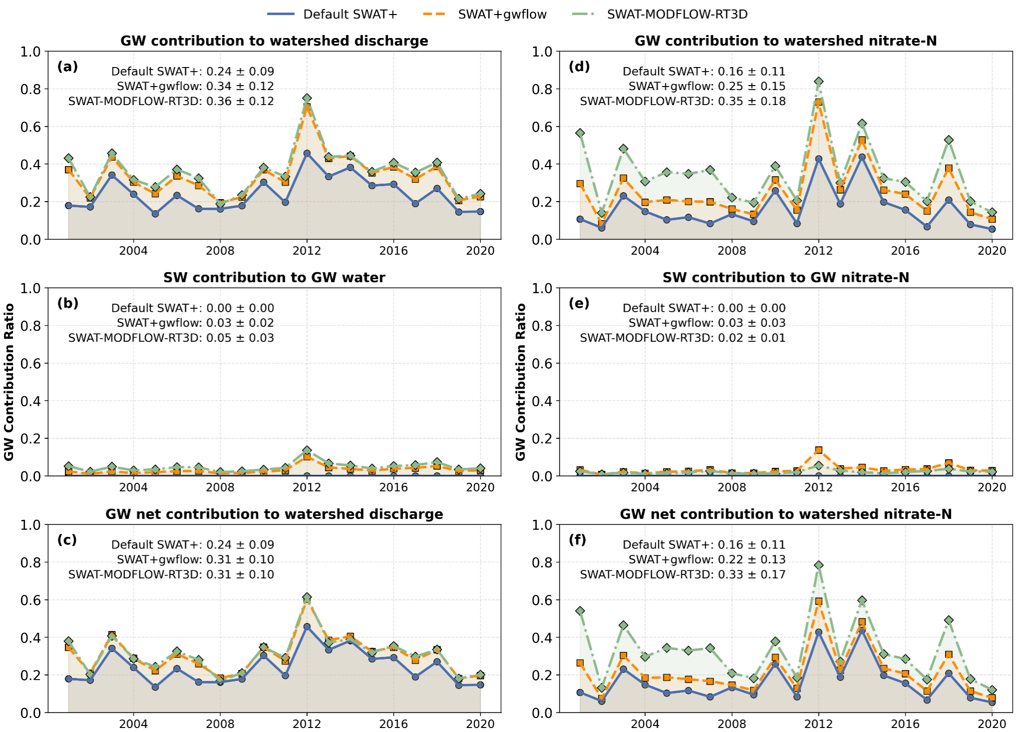

Figure 12. Temporal dynamics of groundwater contributions to watershed hydrology and nitrate-N transport across three modeling frameworks. The left column (a–c) shows groundwater contribution ratios for hydrologic fluxes, including (a) total groundwater contribution to watershed discharge, (b) surface water contribution watershed discharge, and (c) net groundwater contribution. The right column (d–f) presents the corresponding contribution ratios for nitrate-N transport in watershed nitrate-N. Results are compared across the Default SWAT+, SWAT+*gwflow*, and SWAT-MODFLOW-RT3D models. Shaded areas represent interannual variability, and annotated values indicate the mean ± standard deviation over the simulation period.

To further investigate the role of groundwater in water and nitrogen transport at the seasonal scale, monthly dynamics of groundwater–surface water interactions in both hydrology and nitrate-N are

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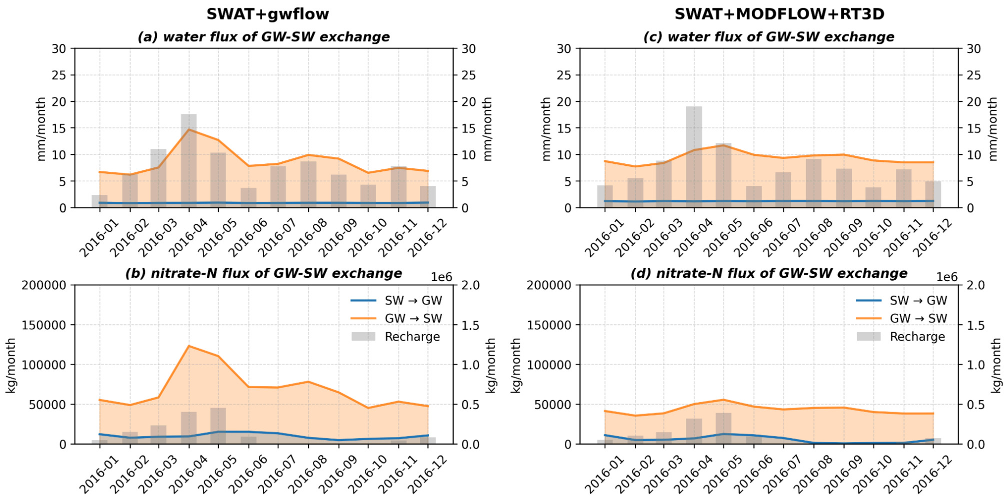
607 presented. Seasonal patterns reveal that groundwater plays a dynamic role in nitrate-N transport (Fig. 13).
608 In both SWAT+*gwflow* and SWAT+MODFLOW+RT3D, groundwater–surface water nitrate-N fluxes vary
609 within the year, with higher groundwater contributions occurring after fertilizer application in late spring
610 and early summer. During this period, nitrate-N delivered from groundwater to the stream can exceed ten
611 times the non-growing-season (November through March of the following year) level, consistent with the
612 elevated groundwater discharge to surface water. In other seasons, groundwater still acts as a net source to
613 the river system, owing to the persistently large groundwater-to-surface water flux (Fig. 13 a and c).



614

615 **Figure 13.** Monthly groundwater–surface water exchange fluxes of water and nitrate-N simulated by
616 SWAT+*gwflow* (a-b) and SWAT+MODFLOW+RT3D (c-d).

617 # 4 Discussion

618 ## 4.1 Surface water–groundwater interaction shapes hydrology and nutrient transport in agricultural
619 watersheds of the U.S. Midwest

620 Surface water–groundwater interactions represent a critical process in typical agricultural
621 watersheds of the U.S. Midwest. In central Illinois, shallow aquifers are hydraulically connected to river
622 systems. The region is characterized by glacial deposits with interbedded sand and gravel layers, which
623 facilitate exchange between streams and groundwater (Panno et al., 1994; Herzog et al., 2002). The
624 geological setting, together with seasonal climate variability, result in both gaining and losing stream
625 conditions. In addition, extensive agricultural drainage systems (e.g., tile drainage) further modify
626 subsurface hydrology and enhance connectivity between soil water, groundwater, and streams. These
627 factors collectively lead to dynamic, bidirectional exchange processes, including baseflow contributions,
628 stream leakage, and bank storage (Schilling and Helmers, 2008; Sophocleous, 2002).

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The study watershed is characterized by strong groundwater–surface water interactions. Unlike systems where groundwater contributes primarily to streamflow but little nitrate-N, groundwater in this watershed serves as an important source of both streamflow and nitrate-N (Fig. 12). The simulated groundwater contribution to streamflow is comparable to the reported baseflow index for this region (Addor et al., 2017), supporting the representation of groundwater as a dominant source sustaining streamflow in the watershed. In addition, the simulated magnitude of groundwater nitrate-N contributions is broadly consistent with previous estimates, which were also used as a soft constraint during model calibration (Table S2). The combination of substantial groundwater discharge and elevated groundwater nitrate-N concentrations results in considerable nitrate-N delivery to the stream. Although denitrification removes part of the nitrate-N during subsurface transport, the large groundwater fluxes appear to outpace this attenuation, allowing a significant fraction of nitrate-N to reach the stream network (Fig. 6 and Fig. 7). The role of groundwater in nitrate–N cycling is temporally dynamic when examined at finer time scales. Nitrate-N inputs from spring fertilizer application are transported downward through recharge, producing a delayed increase in groundwater nitrate-N concentrations that persists into the summer. This lagged response reflects the time required for solute transport through the soil profile and shallow aquifer. As streamflow declines during this period, recharge from surface water to groundwater diminishes, and groundwater discharge becomes the dominant pathway sustaining streamflow. The nitrate-N stored in the aquifer is then gradually released to the stream, so groundwater is maintained as the principal source of stream nitrate-N under baseflow-dominated conditions year-round (Fig. 13).

These results emphasize that groundwater functions as an integral component of watershed nitrogen cycling by regulating both the storage and delayed release of nitrate-N. The delayed transport and seasonal release of nitrate-N from groundwater, combined with the substantial contribution of groundwater to watershed nitrate-N export, suggest that nitrogen losses to streams cannot be fully mitigated by short-term surface water controls alone. From a process perspective, reducing nitrate-N leaching at the source, particularly through optimized fertilizer timing and application rates, as well as practices that enhance nitrogen removal in the soil, such as enhanced denitrification and plant uptake (Chandrasoma et al., 2019; Hanrahan et al., 2018; Nietch et al., 2024), can help limit groundwater nitrate-N accumulation and its subsequent release to streams during baseflow-dominated periods. However, improvements in stream water quality may lag for years to decades because of legacy nitrate-N stored in groundwater (Liu et al., 2024).

4.2 Model structural controls on simulated groundwater and nitrate-N dynamics

Different representations of groundwater systems, including their discretization schemes, governing equations, numerical implementations, and groundwater–surface water interaction mechanisms, even within the same model family where land surface and river processes are shared, can

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lead to substantially different simulation outcomes. The three models evaluated here represent progressively increasing levels of structural complexity in groundwater simulation, ranging from the conceptual groundwater module in the default SWAT+, to the distributed groundwater formulation in SWAT+*gwflow*, and finally to the coupled groundwater flow and reactive transport framework in SWAT+MODFLOW+RT3D. This progression provides an opportunity to evaluate how increasing physical realism influences not only predictive performance but also the representation of subsurface hydrological and biogeochemical processes.

Models with more advanced and physics-based groundwater modules (i.e., SWAT+*gwflow* and SWAT+MODFLOW+RT3D) generally outperform the default SWAT+ in representing groundwater processes, particularly in capturing temporal groundwater head dynamics and resolving individual groundwater flow components. The use of a conceptual governing equation can lead to unrealistic representations of groundwater head dynamics. The default SWAT+ framework employs a linear reservoir model to simulate groundwater head dynamics (Equation S1), rather than the physically based formulation of Darcy's law adopted in SWAT+*gwflow* and SWAT+MODFLOW+RT3D. Furthermore, the finest spatial unit for simulating groundwater processes in SWAT+ is limited to the HRU scale. As a result, a critical structural limitation rendered is that these discretized aquifer units are spatially disconnected, with each unit functioning as an independent 'lumped' bucket to regulate groundwater mass storage. While this governing approach effectively captures long-term responses to recharge at coarse temporal resolutions (Melaku and Wang, 2019; Vazquez-Amábile and Engel, 2005), it often fails to represent realistic daily fluctuations and typically mis-represents groundwater residence time. Specifically, the lack of aquifer lateral flux exchange can trigger the "sawtooth" response to recharge events, resulting in abrupt groundwater level increases followed by gradual recession (Fig. S4). These deficiencies align with findings by Bailey et al. (2020b), who highlighted the limitations inherent in SWAT+'s simplified governing equations and its underlying assumptions regarding aquifer connectivity.

Notably, despite sharing similar conceptual foundations and calibration targets, these two advanced models, SWAT+*gwflow* and SWAT+MODFLOW+RT3D, can produce different groundwater dynamics because they represent groundwater discharge processes differently. SWAT+*gwflow* includes a saturation-excess mechanism that allows groundwater to discharge to the land surface, and then to nearby channels, when the water level intersects exceeds the land surface, even in areas without artificial drainage. In contrast, SWAT+MODFLOW+RT3D does not explicitly represent this pathway. Consequently, in locations lacking drains or stream connections (e.g., non-agricultural land), excess recharge can continue to accumulate until groundwater heads rise above the land surface (Fig. 8). This structural difference influences the spatial distribution of groundwater levels and highlights how alternative representations of groundwater discharge processes can affect model behavior.

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Different model structures can lead to fundamentally different representations of subsurface flow partitioning. In the default SWAT+, groundwater contributions to surface water are aggregated into a single flux, commonly referred to as baseflow. This lumped representation limits the model's ability to distinguish among underlying physical processes. In contrast, SWAT+*gwflow* and SWAT+MODFLOW+RT3D explicitly simulate groundwater flow driven by hydraulic gradient, allowing groundwater to exchange with streams and contribute to tile drainage where appropriate. These models also allow for interactions between aquifer systems and surface features such as canals and wetlands, providing a more physically based and process-explicit representation (Abbas et al., 2025; Wilsnack et al., 2001). In addition, the representation of surface water contributions to groundwater is largely absent in the default SWAT+. Although channel seepage is calculated, this flux is not integrated into the groundwater mass balance and is instead estimated empirically based on streambed hydraulic conductivity. This structural limitation can lead to unrealistic simulations in regions where groundwater recharge from surface water plays a significant role.

Although the three models achieved comparable performance in simulating groundwater nitrate-N concentrations (Fig. 9), this agreement is likely attributable, in part, to calibration against the available observations. Similar model performance therefore does not imply that the underlying reactive transport processes are represented in the same way. Among the three solute transport representations, SWAT+*gwflow* and SWAT+MODFLOW+RT3D provides similar advanced representation of subsurface biogeochemical processes, which may offer advantages in capturing spatial variability in regions with pronounced subsurface heterogeneity. Given its modular implementation within SWAT+, SWAT+*gwflow* offers a more efficient alternative, particularly for watersheds with a single-layer aquifer system.

4.3 Model structural choices in groundwater representation and their implications for agricultural management

The three model configurations exhibit distinct strengths and limitations, and simpler model structures can still offer important advantages depending on the application context. For example, in a data-scarce region where the objective is to estimate groundwater recharge fluxes or approximate the long-term variability of groundwater discharge to streams, our results suggest that it is not necessary to employ a computationally intensive grid-based groundwater module; instead, the default model configuration is sufficient for this purpose (Fig. 10 and Fig. 11). In addition, our results suggest that increased model complexity does not necessarily lead to improved representation of physical processes. Although SWAT+MODFLOW+RT3D has the most complex model structure, its representation of groundwater dynamics and groundwater–surface water and nitrate-N exchanges appears comparable to that of SWAT+*gwflow* in our study area, which is characterized by both unconfined and confined aquifers. This outcome may be attributed to several factors. First, groundwater–surface water interactions in the study area are dominated by shallow flow systems, reducing the need for highly detailed subsurface representation. Second, groundwater recharge and associated nitrate-N inputs are primarily controlled by land surface processes, which are relatively consistently represented across all models, thereby limiting divergence in simulated fluxes. In addition, parameter uncertainty and spatial discretization at the watershed scale may mask the advantages of more complex model structures. Furthermore, calibration against observed groundwater and stream metrics constrains model outputs toward similar magnitudes, despite differences in internal process representation. Finally, the evaluation focuses on integrated responses (e.g., streamflow and nitrate-N loads), which may be less sensitive to structural differences in subsurface modeling.

From a water resources and water quality management perspective, model selection should also account for regional characteristics. For example, in arid and semi-arid regions where streams are often losing and recharge groundwater, as well as in settings such as alluvial aquifers (e.g., the Mississippi River alluvial aquifer), areas with intensive human activity, or streambeds with high permeability, surface water can exert a strong influence on groundwater dynamics (Sophocleous, 2002; Zhao et al., 2026). In such cases, it is essential to adopt models that can provide a more robust basis for informing targeted water and nutrient management decisions over complex landscapes, particularly in systems where groundwater–surface water interactions are significant.. Furthermore, if the objective is to investigate hotspots of groundwater denitrification or assess groundwater-related greenhouse gas emissions, the use of models with grid-based representations and more comprehensive process descriptions becomes necessary. Computational cost is another critical factor in model selection and should be evaluated in conjunction with regional groundwater characteristics, model domain size, and spatial resolution. Among the three models considered in this study, only SWAT+*gwflow* has been applied to groundwater simulations across multiple watersheds (Bailey et al., 2023), reflecting a practical balance between computational efficiency and process representation. Although SWAT+*gwflow* employs a grid-based spatial discretization, it utilizes an explicit numerical scheme, which is generally more computationally efficient than implicit approaches. However, the model adopts a simplified representation of subsurface processes. Most notably, the aquifer system is represented as a single layer, limiting its ability to capture vertical heterogeneity and layered flow dynamics. Despite this simplification, SWAT+*gwflow* can be applied at relatively fine spatial resolutions in watershed-scale studies, with grid sizes on the order of a few hundred meters or smaller. As with other distributed hydrologic models, however, applications over large regional or national domains often require coarser spatial resolutions to maintain computational feasibility (Alattar et al., 2020; Maxwell and Condon, 2016; Ma et al., 2026).

In addition to the differences discussed above in how these models represent groundwater components (Fig. 7), they also differ in their ability to characterize groundwater legacy effects. This

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capability is particularly relevant for evaluating the long-term impacts of land-use transitions, such as the conversion of annual row-crop systems to perennial bioenergy crops or other conservation-oriented land uses. Because groundwater nitrate-N stored under historical management practices may continue to discharge to streams for years or decades after land-use change, accurate representation of groundwater transit times and legacy processes is essential for assessing the timing and magnitude of water-quality improvements. Both SWAT+*gwflow* and SWAT+MODFLOW+RT3D, owing to their explicit representation of subsurface structure and stream–aquifer interactions, enable the estimation of groundwater travel time based on flow velocity and travel distance. This capability has important implications for quantifying nitrate–N legacy in groundwater. In contrast, the default SWAT+ lacks this functionality and currently requires coupling with additional modeling approaches (e.g., SAS-based frameworks, Li et al., 2024) to represent legacy processes.

Several limitations should be acknowledged for the current model frameworks. The three models considered in this study adopt a relatively loose coupling between surface and subsurface systems, where the vadose zone and groundwater are primarily linked through recharge fluxes and capillary rise. In reality, the atmosphere–land–groundwater system functions as a continuum, with strong bidirectional interactions across compartments (Berkowitz and Zehe, 2020; Woessner and Poeter, 2020). In particular, plant hydraulic processes, which can play an important role in regulating soil moisture dynamics and mediating groundwater uptake and redistribution, are largely neglected. This simplification may limit the ability of the models to fully capture feedbacks between vegetation, soil water, and groundwater, especially under conditions where plant water use exerts a strong control on subsurface dynamics. Another limitation lies in the simplified representation of reactive transport processes at the watershed scale. Among the three models, SWAT+MODFLOW+RT3D employs the most computationally intensive reactive transport framework; however, it is limited to nitrate-N denitrification, neglecting other potentially important kinetic biogeochemical processes such as nitrification, ammonification, and multi-species nutrient transformations due to computational constraints. While explicitly representing these processes with high realism remains challenging at the watershed scale (Li, 2019), addressing this limitation is critical for improving the mechanistic understanding of nutrient dynamics in future modeling efforts for the SWAT+ model family. In addition, the limited availability of continuous groundwater observations, particularly for groundwater quality, introduces additional uncertainty in model calibration. This constraint is not unique to this study but reflects a broader challenge in hydrological research, especially within the context of Critical Zone studies, where integrated observations across subsurface systems remain sparse and are urgently needed (Brantley et al., 2007; Zhi et al., 2019).

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5 Conclusions

This study integrates physically based modeling with system-level observations to investigate the role of groundwater in a representative agricultural watershed of the U.S. Corn Belt, and quantitatively assesses groundwater's contributions to watershed-scale hydrologic fluxes and nitrate-N dynamics. In addition, we examine how the widely used SWAT+ and its extended model family (SWAT+*gwflow*, SWAT+MODFLOW+RT3D) represent these processes, highlighting their similarities and differences. To our best knowledge, this is the first study to provide a comparative evaluation of SWAT+, SWAT+*gwflow*, and SWAT+MODFLOW+RT3D in simulating groundwater hydrological and nitrate-N transport processes within agricultural watersheds. Our simulation reveals that groundwater contributes substantially to river fluxes of both water and nitrate-N. Importantly, this contribution persists even at the net flux level. Integrated over time, groundwater acts as a consistent net source of nitrate-N to the river network. The magnitude of this source varies at finer temporal scales, strengthening during periods following fertilizer application. All three models reproduce watershed discharge and TN loads with reasonable accuracy, and their estimates of groundwater heads and nitrate-N concentrations are generally within acceptable ranges. However, the semi-empirical structure of the default SWAT+ does not explicitly represent groundwater–surface water exchange processes, which limits its ability to resolve the mechanisms governing interactions between surface and subsurface systems. This limitation persists despite its relatively low computational cost and efficiency compared to more physically based formulations, highlighting a trade-off between process representation and computational demand.

Conservation strategies should account for subsurface processes, particularly denitrification, by promoting practices that increase residence time in the soil–groundwater system and enhance nitrogen attenuation, thereby reducing downstream nitrogen losses. At the same time, the temporally dynamic role of groundwater underscores the need to better align fertilizer applications with hydrologic conditions to reduce mobilization risks. Finally, differences among model structures suggest that while simpler tools such as the default SWAT+ are useful for efficient watershed-scale estimates, more physically based models are better suited to capture groundwater–surface water interactions and to inform targeted, process-based conservation strategies.

Code and data availability

The source code for SWAT+ (61.0.1) and SWAT+*gwflow* (61.0.1) is publicly available at https://github.com/swat-model/swatplus. The source code for coupling SWAT+MODFLOW+RT3D is available at https://zenodo.org/records/14674981. Data will be made available on request.

Author contributions

YJW: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Visualization, Writing – original draft. **BP:** Conceptualization, Methodology, Validation, Supervision, Resources, Funding acquisition, Writing – review & editing. **MQJ:** Validation, Writing – review & editing. **ZWM:** Validation, Writing – review & editing. **QYZ:** Data curation, Writing – review & editing. **RB:** Methodology, Validation, Writing – review & editing. **DA:** Data curation, Writing – review & editing. **JY:** Validation, Writing – review & editing. **KG:** Writing – review & editing. **MP:** Writing – review & editing. **YXS:** Data curation, Writing – review & editing.

Competing interests

The authors declare there are no conflicts of interest for this manuscript.

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