



Enhancing global water cycle representation through two-way coupling of VIC-WUR and MODFLOW 6

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Abstract. Groundwater is a critical component of the global water cycle, sustaining streamflow during dry periods and supporting evapotranspiration where water tables are shallow. However, in many global hydrological models, groundwater processes are represented in a simplified way, which limits the simulation of water tables, lateral flow, groundwater–river exchange, and capillary rise. Here, we present VIC-WUR v3.0, a new global hydrological modelling framework in which the land-surface model VIC-WUR is coupled with MODFLOW 6, a physically based groundwater flow model. Compared with many existing global hydrological models, the new framework explicitly simulates transient groundwater flow and introduces a groundwater-depth-dependent capillary rise parameterisation constrained by soil hydraulic properties.

The coupled model is applied globally at 5 arcmin resolution under naturalised conditions for 1980–2009. The coupled model results are broadly consistent with the large-scale behaviour reported by other global hydrological and groundwater modelling studies. Groundwater recharge falls within the range of existing global model estimates, while VIC-WUR v3.0 tends to simulate comparatively higher recharge. Simulated capillary rise is spatially concentrated rather than spatially widespread, emerging mainly in regions with shallow groundwater where it can support soil moisture and evapotranspiration. Relative to the uncoupled VIC-WUR configuration, the coupled simulation also improves the representation of seasonal river discharge dynamics, particularly under low-flow conditions. These results show that VIC-WUR v3.0 provides a more physically based representation of groundwater–surface water interactions at the global scale and highlights the importance of capillary rise in shallow-groundwater environments. The model offers a new platform for investigating water availability under future human impacts, climate change, and land-use change.

1 Introduction

Reliable information on global freshwater availability is crucial for effective water resource management and food security. Quantifying current and future water scarcity, as well as the impacts of human water use, remains a challenge for hydrologists and policymakers (Caretta et al., 2022; Yang et al., 2021). Traditional global hydrological models (GHMs) have typically focused on land surface processes and tended to oversimplify groundwater processes (Sood and Smakhtin, 2015; Gleeson



et al., 2021). However, groundwater plays a critical role in sustaining streamflow during low-flow periods (Johnson et al., 2023; Xie et al., 2024; Carroll et al., 2024; Marinelli et al., 2025). Recent research also highlights that groundwater abstraction significantly influences surface streamflow (de Graaf et al., 2019, 2024). To effectively meet future global water demands, it is therefore essential to jointly consider surface water and groundwater resources (Scanlon et al., 2023). As a result, a new generation of GHMs are increasingly evolving from primarily surface-based simulations to integrated surface-groundwater flow models (Sutanudjaja et al., 2018; Guillaumot et al., 2022; Reinecke et al., 2019b).

Nonetheless, the representation of groundwater systems within GHMs remains constrained by both data availability and the conceptual approach used in the groundwater model (Reinecke et al., 2019a; Gleeson et al., 2021). Consequently, groundwater components have been incorporated into GHMs at varying levels of complexity, depending on each model's context and specific objectives (Telteu et al., 2021). Typically, GHMs integrate surface and groundwater models through two main interactions: (1) focused recharge and baseflow exchange between surface water bodies and groundwater aquifers; (2) diffuse recharge and capillary flux between the vadose and saturated zones. These four fluxes form the key links that couple surface and groundwater systems (Döll and Fiedler, 2008; de Graaf et al., 2017).

The coupling of focused recharge and baseflow has been increasingly implemented in several leading GHMs, enabling more realistic simulations of groundwater–stream interactions, particularly in basins with strong hydrological connectivity (Zheng et al., 2025; Guillaumot et al., 2022; Chenjerayi Guzha and Hardy, 2010). However, the representation of capillary rise, which is an essential upward flux from the saturated zone to the root zone, remains limited or overly simplified in many GHMs (Koirala et al., 2019). One common approach to representing capillary rise in GHMs is to estimate it as an upward flux from the saturated zone based on water table depth and soil texture, and then subtract it from gravity drainage to compute a net recharge passed to the groundwater module (Sutanudjaja et al., 2018). This method often lacks dynamic adjustment to temporal variations in water table depth. Another approach is to compute capillary rise within the groundwater model itself, typically via a drain-type mechanism, with the resulting upward flux returned to the root zone as a moisture source for transpiration (Guillaumot et al., 2022). However, such implementations may not impose a physically based upper limit on capillary flux and often overlook dynamic constraints from soil hydraulic properties, which can lead to overestimation of upward flow under saturated or near-saturated conditions.

The VIC-WUR model, which is an extension of version 5 of the Variable Infiltration Capacity (VIC) model (Hamman et al., 2018), has been widely used to assess human impacts on global water resources (Droppers et al., 2020). It is considered one of the leading GHMs, with applications across the globe. In addition to the original VIC-5 framework, VIC-WUR introduces several enhanced components, including (1) an integrated river routing module, (2) sector-specific surface and groundwater use modules, (3) an environmental flow requirement module, and (4) dam operation modules. The model has been applied to simulate the effects of climate change and human interventions on current and future water resources, as well as sectoral water scarcity, at a spatial resolution of 30 arcmin globally (Droppers et al., 2020) and at finer resolutions in agricultural hotspot regions (Droppers et al., 2021; Yousefi Sohi et al., 2024; Yang et al., 2025). One distinctive feature of VIC-WUR is its foundation in a land surface modelling framework (Liang et al., 1994). As it has been further developed into a hydrological model, it accounts for both the surface energy and water balances. This provides a more robust representation of evapotranspiration



processes than models that rely solely on the water balance. Consequently, VIC-WUR is particularly well suited to simulate the influence of agricultural activities on global water availability and to explore the implications of water scarcity for global food security, as irrigation, vegetation dynamics and evapotranspiration are consistently constrained by both water availability and surface energy balance (Droppers et al., 2021).

However, VIC-WUR also has several limitations. Its representation of groundwater is highly simplified, relying on an unlimited bucket model that does not constrain groundwater storage or flow by physical properties of the subsurface. This oversimplification limits the model's ability to simulate key groundwater processes, such as lateral flow and depletion, and restricts its suitability for applications that require physically realistic subsurface dynamics. In addition, the influence of capillary rise on plant transpiration is not explicitly considered, meaning that upward moisture fluxes from the saturated zone to the root zone are not fully represented in the soil–vegetation–atmosphere interactions.

To address these shortcomings, the present study introduces VIC-WUR v3.0, a new version of the VIC-WUR model that is coupled with a physically based groundwater flow model, i.e., MODFLOW 6 (Langevin et al., 2017). This updated framework integrates a physically based groundwater flow model with the land surface processes of VIC-WUR, enabling a more realistic simulation of groundwater–surface water interactions at the global scale. Crucially, VIC-WUR v3.0 includes a water table depth–dependent capillary rise formulation, constrained by soil hydraulic properties, to ensure that the upward flux is physically realistic and dynamically responsive. This work aims to enhance the physical realism of GHM–groundwater coupling and to provide a new tool for integrated assessments of global water scarcity under changing climate and land use conditions. The physically consistent representation of groundwater flow and capillary rise adopted here is designed to support model inter-comparison and ensemble-based impact assessments, and VIC-WUR v3.0 also contributes to coordinated inter-model efforts and ensemble analysis, such as the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Groundwater sector (Reinecke et al., 2026).

To demonstrate the model structure and its capabilities, this paper is organized as follows. Section 2 presents the VIC-WUR v3.0 modelling framework, including the core features adopted from the previous version of VIC-WUR, the key developments introduced in v3.0, the design of the underlying MODFLOW 6 groundwater model, and the technical implementation of the coupling interface. Section 3 describes the global model application, including the model setup, input data, and model execution. Section 4 presents the global simulation results, focusing on groundwater recharge, water table depth, capillary rise, and groundwater–surface water exchange. Section 5 discusses the broader implications of the results, the main sensitivities and uncertainties of the coupled modelling framework, and pathways for future model development.

2 Model Infrastructure and Development

2.1 Evolution from VIC to VIC-WUR model

The Variable Infiltration Capacity (VIC) model has a long-standing history as a macro-scale hydrological model, which was initially developed to simulate the vertical movement of water and energy within the land surface system (Liang et al., 1994). Its origins trace back to earlier versions where the model was primarily used as a land surface model, focusing on the exchange



between land and atmosphere. Over time, VIC evolved into a stand-alone hydrological model capable of representing complex hydrological processes across large spatial scales.

A significant advancement came with the release of VIC version 5 (VIC-5), which improved the model infrastructure substantially (Hamman et al., 2018). These enhancements included adopting the NetCDF format for efficient input and output data handling and implementing parallel processing using message passing interface (MPI), which considerably reduced computation times for large-scale simulations. A key change in VIC-5 was the shift from a ‘time-before-space’ to a ‘space-before-time’ processing order, enabling interactions between grid cells at each time step. This development facilitated the integration of river routing and other spatially distributed processes within the model, which were previously handled as offline post-processing steps.

Building upon VIC-5, VIC-WUR represents a comprehensive extension tailored to assess anthropogenic impacts on global water resources (Droppers et al., 2020). The VIC-WUR model integrates several new modules to simulate human water use sectors, including irrigation, domestic, industrial, energy and livestock water demands, as well as environmental flow requirements and dam operations. These additions allow VIC-WUR to capture the dynamic interplay between natural hydrological processes and human interventions, providing a more holistic and realistic representation of global water resource availability and use.

2.2 Groundwater representation in VIC-WUR and MODFLOW integration

The original VIC-WUR employs a simplified linear unlimited bucket model to represent groundwater. In this representation, groundwater flow is simulated through a conceptual bucket associated with the lowest soil layer, neglecting spatial variability and detailed aquifer properties (Droppers et al., 2020). This simplification limits the model’s ability to realistically simulate groundwater depletion and groundwater–surface water interactions. To overcome this limitation, we coupled VIC-WUR with MODFLOW, a physically based groundwater flow model.

To realise this coupling, modifications were made to fluxes and water transfer processes within VIC-WUR to enable communication with MODFLOW. In the original VIC-WUR, the lowest soil layer is used to mimic groundwater storage and to generate subsurface flow contributing to streamflow. In the coupled model configuration, these processes are replaced by MODFLOW. Instead, VIC-WUR calculates groundwater recharge at the lower boundary of the soil column using an analytical one-dimensional Richards equation (Richards, 1931), in which unsaturated hydraulic conductivity is described by the Brooks-Corey relationship (Brooks, 1964). This groundwater recharge is then passed to MODFLOW as an input source term, while in the uncoupled VIC-WUR configuration subsurface flow continues to be computed internally and contributes to streamflow. In this way, a physically consistent coupling between the vadose zone and the saturated zone is established. Further details can be found in Appendix A2

For the groundwater component, we adopted the global two-layer transient groundwater model developed by de Graaf et al. (2017), which was previously coupled with PCR-GLOBWB (Sutanudjaja et al., 2018). We retained the main aquifer properties from the original implementation, including permeability, aquifer thickness, transmissivity and storage coefficients, derived from global datasets (Gleeson et al., 2011; Huscroft et al., 2018). Details of the model inputs are in Appendix A1. In addition,



125 we upgraded the groundwater model from MODFLOW 2005 to MODFLOW 6, using the Node Property Flow (NPF) package
for enhanced flexibility in groundwater flow simulation (Langevin et al., 2017).

To simulate capillary rise, we used the MODFLOW Evapotranspiration (EVT) package, as groundwater evaporation simulated by EVT closely resembles the physical mechanisms governing capillary rise. Specifically, the EVT package depends on three parameters: (1) the evapotranspiration (ET) surface elevation, (2) the maximum ET flux rate, and (3) the ET extinction
130 depth (Figure 1). Analogously, capillary rise was represented by defining three corresponding parameters: (1) the bottom depth of the lowest soil layer below land surface (Z_{bot}), (2) the maximum capillary rise height (h_{cmax}), and (3) the maximum capillary flux (q_{cmax}). In this analogy, the ET surface elevation corresponds to the bottom depth of the lowest soil layer, the ET extinction depth corresponds to the maximum capillary rise height, and the maximum ET flux corresponds to the maximum capillary flux.

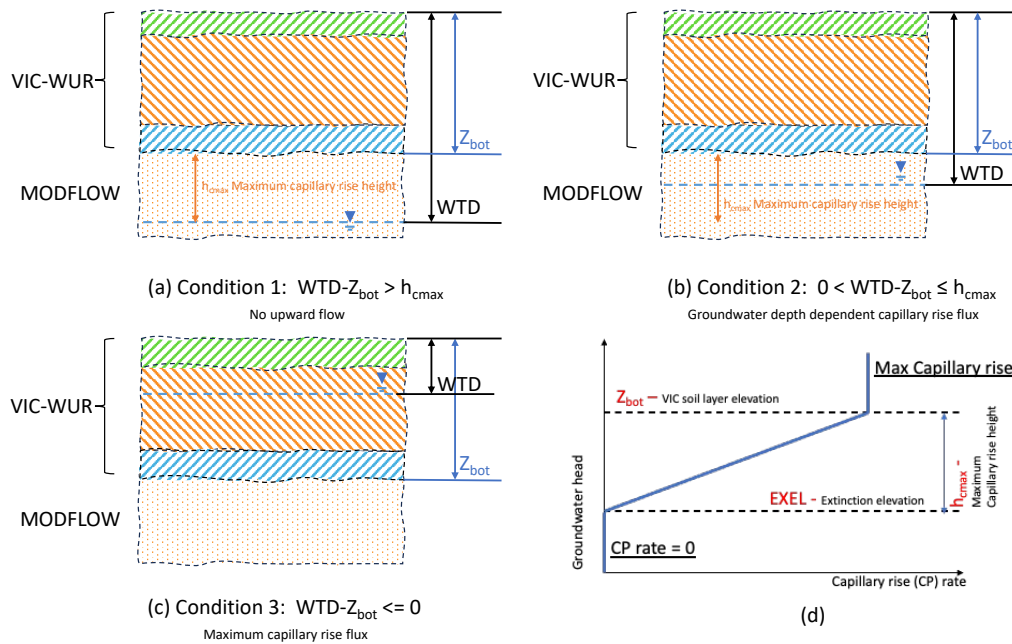


Figure 1. Conceptual diagram of the groundwater-depth-dependent capillary rise parameterisation implemented in the coupled VIC-WUR–MODFLOW framework. Panels (a)–(c) show the three hydrological conditions controlling upward flux: no capillary rise, linearly depth-dependent capillary rise, and maximum capillary rise flux. Panel (d) presents the corresponding conceptual relationship between water table depth and capillary rise (CP) rate.



$$q_c = \begin{cases} q_{c\max}, & \text{if } \text{WTD} \leq Z_{\text{bot}}, \\ q_{c\max} \left(1 - \frac{\text{WTD} - Z_{\text{bot}}}{h_{c\max}} \right), & \text{if } Z_{\text{bot}} < \text{WTD} \leq Z_{\text{bot}} + h_{c\max}, \\ 0, & \text{if } \text{WTD} > Z_{\text{bot}} + h_{c\max}. \end{cases} \quad (1)$$

where q_c and $q_{c\max}$ are capillary fluxes [L T^{-1}], $h_{c\max}$ is the maximum capillary rise height [L], WTD is water table depth below land surface [L], and Z_{bot} is the bottom depth of the lowest soil layer below land surface [L]. Equation 1 therefore describes three regimes: no capillary rise when groundwater is too deep, depth-dependent capillary rise when groundwater remains within the capillary influence zone, and maximum capillary rise when groundwater reaches the bottom of the lowest soil layer.

Two critical parameters, $h_{c\max}$ and $q_{c\max}$, were estimated following Liu et al. (2014) and Eagleson's capillary flux equation Eagleson (1978), respectively, as applied by Koirala et al. (2019). Both parameters are prescribed as spatially distributed, grid-cell-specific values derived from soil texture and remain static during the simulation. Further details on the calculation of the three primary capillary rise parameters (Z_{bot} , $h_{c\max}$, and $q_{c\max}$) are provided in Appendix A3. By integrating this process, the coupled model can more realistically represent the upward movement of water from the saturated zone to the root zone, which is critical for simulating soil moisture dynamics and plant water availability in regions influenced by shallow groundwater.

2.3 VIC-WUR and MODFLOW coupling framework

Fig. 2 illustrates the overall coupling framework, its principal components, and the monthly exchange of fluxes between the land-surface model (VIC-WUR), the groundwater model (MODFLOW) and the river routing module.

In practice, VIC-WUR is executed first on a daily time step to resolve precipitation, evapotranspiration, soil-moisture dynamics, and internally routed surface flow. At the end of each calendar month, VIC-WUR aggregates two key fluxes: (1) groundwater recharge and (2) the total surface streamflow exiting each grid cell. These monthly totals are then provided to MODFLOW as input for a one-month stress period, using the RCH (recharge) and RIV (river leakage) packages, respectively. During each monthly stress period, MODFLOW solves transient two-layer groundwater flow, thereby updating water tables and subsurface storage. From this solution, it computes (1) baseflow, representing groundwater discharge to the river network, and (2) capillary rise, representing upward moisture transfer from the water table towards the soil column in VIC-WUR. These fluxes are then passed back to VIC-WUR at the start of the following month.

Within the next daily VIC-WUR run, the MODFLOW-derived baseflow is added to each river reach prior to routing, thereby augmenting surface discharge with groundwater contributions. Simultaneously, the capillary rise flux is applied to the lowest soil layer as an additional source term. Any excess moisture beyond the storage capacity of that soil layer is redistributed upward into overlying layers in accordance with VIC-WUR's soil-moisture framework.

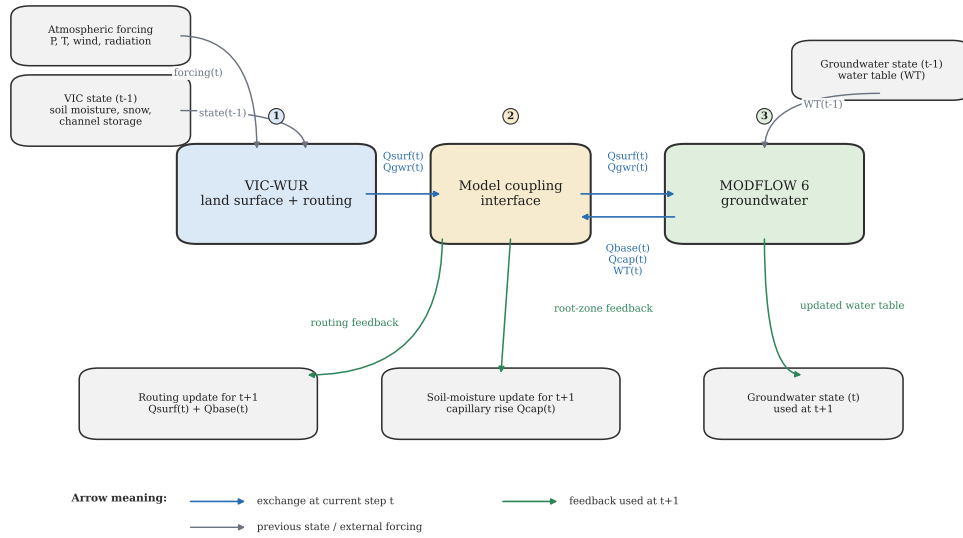


Figure 2. Schematic overview of the monthly coupling between VIC-WUR and MODFLOW 6. At coupling step t , VIC-WUR provides surface discharge (Q_{surf}) and groundwater recharge (Q_{gwr}) to MODFLOW 6, while MODFLOW 6 returns baseflow (Q_{base}), capillary rise (Q_{cap}), and water tables (WT) updates for the next step ($t + 1$). Here, P is precipitation, T is air temperature, Q_{surf} is surface discharge, Q_{gwr} is groundwater recharge, Q_{base} is baseflow, and Q_{cap} is capillary rise.

We use a daily VIC-WUR time step to resolve fast land-surface processes and a monthly coupling interval to (a) align with typical MODFLOW stress-period lengths, (b) avoid daily noise that the groundwater model cannot represent meaningfully, and (c) limit computational cost. This arrangement maintains strict water balance consistency between the atmosphere, soil column, aquifer, and river network, while retaining the individual strengths and modular flexibility of the VIC-WUR and MODFLOW codes.

3 Model Application

3.1 Model setup

The coupled model is applied over the global domain at a spatial resolution of 5 arcmin, which corresponds to roughly 10 km at the equator. VIC-WUR is executed on a latitude-longitude grid that follows the WGS84 reference system, whereas MODFLOW operates on a Cartesian grid. Consequently, areal fluxes generated by VIC-WUR are converted between the two grid systems in an area-consistent manner before they are supplied to MODFLOW and vice versa to maintain water balance consistency across the land surface and subsurface.



175 The simulation covers the period from January 1980 to December 2009, a span that captures recent multi-decadal climate variability. Human impact modules are not activated in the current setup, so the simulations represent naturalised conditions. Prior to the analysis period, VIC-WUR is spun up for 10 years by recycling meteorological forcing from 1980 to 1989, allowing soil moisture and river discharge to stabilize. A steady-state solution of MODFLOW provides initial water tables. This configuration allows soil moisture, water tables and surface flows to reach dynamic equilibrium with the prevailing climate conditions while maintaining consistency between the land-surface and groundwater components.

Meteorological forcing is provided by the ERA5-Land reanalysis (Copernicus Climate Change Service (C3S), 2019), originally at 6 arcmin resolution and subsequently downscaled to 5 arcmin to match the model grid. Daily precipitation, air temperature, shortwave and longwave radiation, wind speed and specific humidity are derived from the hourly data. Land cover types are based on the MODIS satellite product MCD12Q1.061 (Friedl and Sulla-Menashe, 2015), aggregated from 500 m to 5 arcmin. Leaf Area Index (LAI), albedo and canopy coverage are derived from the MODIS satellite product MCD15A2H.061 (Myneni et al., 2021), MCD43A3.061 (Schaaf and Wang, 2021) and MOD13A1.061 product (Didan, 2021), respectively. Soil parameters are based on the WISE soil property database from ISRIC (Batjes, 2016) using the Multiscale parameter regionalization (MPR) method (Samaniego et al., 2010). Topographic variables including the surface elevation and flow drainage map are based on the HYDROSHEDS v1 (Lehner et al., 2008). MODFLOW aquifer parameters, including aquifer thickness, hydraulic conductivity, and storage coefficients, follow the global groundwater model setup of de Graaf et al. (2017).

Model evaluation is based on comparisons with observed river discharge and groundwater observations. River discharge is evaluated against records from the Global Runoff Data Centre (GRDC) (Global Runoff Data Centre (GRDC), 2025). Simulated water tables are compared with available large-scale groundwater observation-based datasets (Fan et al., 2013; Jasechko et al., 2024). The observed water tables, averaged over the model period, are largely limited to northern Europe and North America. We evaluated the water tables using the coefficient of determination between the simulated and observed values and the deviation within one order of magnitude. In addition, simulated water table depth and groundwater recharge are compared with results from other global groundwater models participating in the ISIMIP groundwater sector (Reinecke et al., 2026).

3.2 Simulation execution and performance

200 Simulations were performed on the Wageningen University & Research high-performance computing cluster Anunna, utilizing AMD EPYC 7713 processors. These 64-core processors operate at a base clock frequency of 2.0 GHz with a maximum boost frequency of 3.675 GHz. Each simulation was executed in parallel on a single node using 8 MPI processes with 8 OpenMP threads per process, thereby utilizing a total of 64 cores. Model throughput for the VIC-WUR component on the aforementioned hardware is approximately 2.2 simulated years per day of wall-clock time, which is an average value over the total simulation runtime. This includes a monthly re-initialization phase that occurs after the MODFLOW calculations, to resume the operation of VIC-WUR. This re-initialization phase entails loading a relatively large statefile of approximately 90 GB into working memory and accounts for more than 60% of total runtime. Total peak memory usage is approximately 220 GB.



The MODFLOW component was run on the same hardware, but runs serially (i.e. on a single core) and averages a throughput of 16.1 years/day for the coupled simulations.

210 4 Results

4.1 Groundwater recharge

Simulated groundwater recharge patterns broadly mirror the large-scale distribution of precipitation and evapotranspiration (Fig. 3a). Mean annual recharge is highest in humid tropical and monsoon-dominated regions, including the Amazon, South Asia, and parts of northern Australia, whereas much lower values occur across arid and semi-arid interiors. Across active
215 land cells, the long-term mean annual groundwater recharge for 1980–2009 has a global arithmetic mean of 231.6 mm yr⁻¹, with a median of 131.2 mm yr⁻¹. The recharge distribution is spatially heterogeneous, with an interquartile range of 24.7–299.4 mm yr⁻¹, indicating that a limited fraction of humid regions contributes a large share of global recharge.

The analysis of monthly groundwater recharge (Fig. B3) further shows that recharge seasonality is strongest where precipitation is concentrated within a short wet season. This pattern is also consistent with the seasonal amplitude and relative
220 seasonality shown in Fig. 3c,d. This is particularly evident in monsoon systems. In South Asia, mean annual recharge is about 196 mm yr⁻¹, the seasonal amplitude is about 83 mm month⁻¹, and recharge peaks in August. Moreover, about 56% of the annual recharge occurs during the three wettest months. Northern Australia shows a similarly concentrated seasonal regime, with mean annual recharge of about 150 mm yr⁻¹, a seasonal amplitude of about 60 mm month⁻¹, and about 57% of annual recharge occurring during the three wettest months. In the Amazon region, mean annual recharge reaches more than
225 700 mm yr⁻¹ and the seasonal amplitude is about 111 mm month⁻¹, while only about 37% of annual recharge occurs during the three wettest months. This indicates that the Amazon sustains high recharge over a longer effective recharge season, whereas monsoon regions concentrate recharge into a smaller number of months.

Compared with other global groundwater models participating in the ISIMIP groundwater-sector comparison (Reinecke et al., 2026), the coupled VIC-WUR model estimate falls within the same overall order of magnitude but lies toward the upper
230 part of the model ensemble (Fig. 3b). This result suggests that the coupled VIC-WUR configuration produces comparatively strong groundwater replenishment while remaining within the spread of current large-scale model estimates. The relatively high groundwater recharge simulated here likely results from the adopted soil and evapotranspiration parametrization, which together promote infiltration and limit unrealistically large evaporative losses. As a consequence, the model yields higher recharge, shallower water table depths, and greater subsurface water availability.

235 4.2 Water tables

Fig. 4a shows the simulated long-term mean water table depth under natural conditions (i.e., without anthropogenic water use), expressed in meters below land surface. The global patterns are broadly consistent with major hydrogeological and climatic controls. Shallow water table depths are widespread in coastal plains and large alluvial basins, for example, for the Mississippi

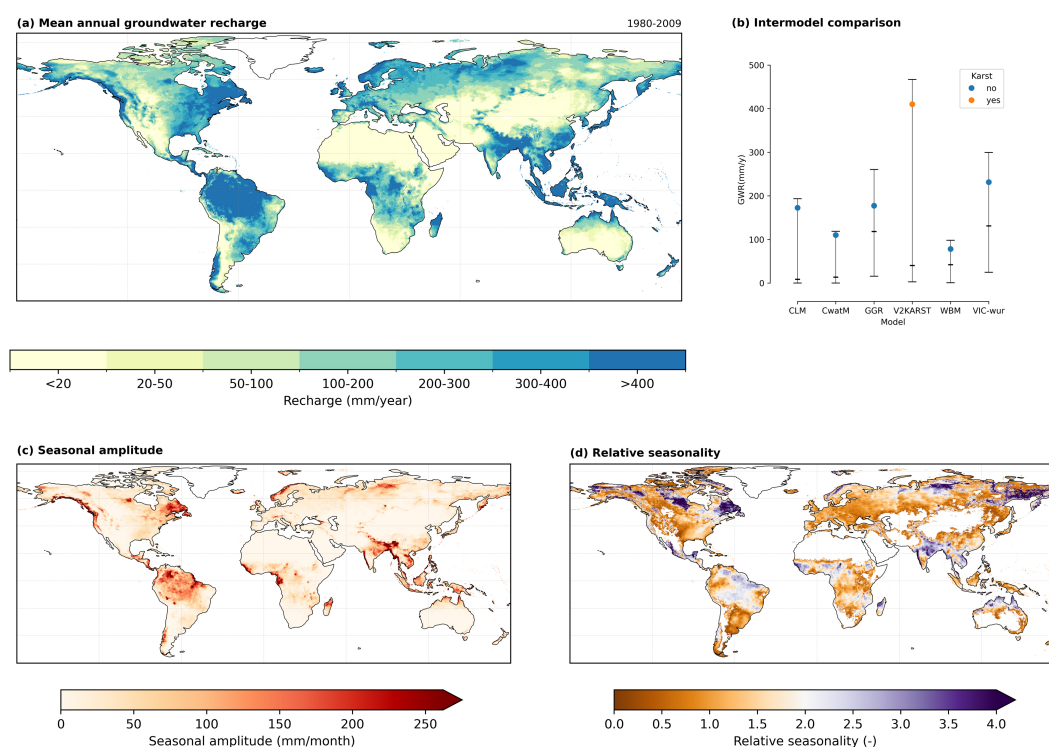


Figure 3. Groundwater recharge characteristics in the coupled VIC-WUR simulation. **(a)** Long-term mean annual recharge for 1980–2009 (231.6 mm yr^{-1}). **(b)** Intermodel comparison of global groundwater recharge statistics from the ISIMIP groundwater model ensemble, with the coupled VIC-WUR estimate replacing the original VIC-WUR steady-state entry. **(c)** Seasonal amplitude of groundwater recharge, calculated as the difference between the maximum and minimum monthly climatological recharge (mm month^{-1}). **(d)** Relative seasonality of groundwater recharge, calculated as seasonal amplitude divided by mean monthly recharge.

Embayment, the Indus and Ganges basins, and Po Valley. By contrast, arid interiors and major mountain belts tend to exhibit substantially deeper water table depths.

Regional variability is primarily controlled by recharge and topography. Areas with high recharge and relatively flat terrain, such as the Amazon lowlands, generally show shallow water tables, whereas regions with stronger topographic gradients promote lateral groundwater redistribution away from elevated terrain. In deserts and high mountain regions, where recharge is limited, simulated water tables are much deeper, and water tables are more weakly tied to local surface topography.

Across all active cells, the global area-weighted mean water table depth is 139.7 m, whereas the global median is 48.6 m, indicating a strongly right-skewed distribution with a relatively small fraction of very deep groundwater systems. The interquartile range spans 16.5–152.1 m. Approximately 14.1% of active cells have a mean water table depth shallower than 5 m, highlighting the substantial global extent of shallow groundwater systems despite the large global mean depth.



Fig. 4b compares simulated water tables with available reference datasets. Agreement is generally high, with an overall
250 coefficient of determination (R^2) of 0.87. The spread of groundwater-head residuals increases with increasing water table depth,
suggesting that mismatches tend to be larger in regions with deeper groundwater systems (Fig. B5). To further examine whether
model performance varies systematically across climatic settings, we additionally stratified the comparison between simulated
and observed water tables by Köppen–Geiger climate class (Beck et al., 2018). Specifically, the available observation-based
water table data were grouped according to their climate class, and the simulated–observed relationships were then evaluated
255 separately for each group. This analysis shows weaker agreement in several tropical and temperate climate classes, whereas
agreement is generally stronger in arid and continental climates. The full set of climate-class-specific scatter plots is provided
in Appendix B3.

The simulated global water table depth distribution is broadly consistent with previous large-scale studies, including those
from the ISIMIP Groundwater Sector (Reinecke et al., 2026) (Fig. 4c). Relative to G³M (Reinecke et al., 2019b) and GWM (Fan
260 et al., 2013), VIC-WUR tends to produce deeper water table depths. In the ISIMIP groundwater-sector intercomparison, such
differences were discussed in relation to model-specific choices in initial conditions, aquifer parameterization, transmissivity,
and groundwater drainage representation, while noting that forcing differences between models may also contribute.

4.3 Capillary rise

Capillary rise is a spatially concentrated rather than globally widespread groundwater flux in the coupled VIC-WUR simulation
265 (Fig. 5). It occurs primarily in regions with shallow water tables, where upward groundwater movement can support root-zone
moisture and evapotranspiration. Although the global magnitude of simulated capillary rise is much smaller than groundwater
recharge, local and regional contributions can still be hydrologically relevant, especially in dry environments with strong
groundwater–soil coupling. Previous studies have shown that in regions with shallow groundwater, such as the Indus River
Basin, capillary rise can supply 10–40% of total evapotranspiration, particularly during dry periods when other water sources
270 become limited (Kahlow et al., 2005; Ahmad et al., 2002).

In our simulation, the area-weighted mean capillary rise across non-zero capillary rise cells is only $0.056 \text{ mm month}^{-1}$
(0.67 mm yr^{-1}), and only 1.7% of active land cells exhibit non-zero long-term mean capillary rise. This demonstrates that
capillary rise does not act as a diffuse global background flux, but instead appears in geographically restricted hotspots. The
strongest signals are found in Central Asia and West/Central Africa, where long-term mean capillary rise reaches about 0.069
275 and $0.058 \text{ mm month}^{-1}$, respectively. Elevated values are also simulated in Southern South America, western North America,
and parts of the Indian subcontinent.

These patterns indicate that capillary rise is most relevant where shallow groundwater can maintain upward hydraulic gra-
dients toward the soil column. In such regions, including capillary rise in the model improves the physical consistency of
unsaturated–saturated zone interactions by allowing groundwater to contribute directly to soil moisture, evapotranspiration,
280 and the coupled water balance. Even though the global mean flux remains small, the regional hotspots identified here suggest
that capillary rise is an important process for representing groundwater-supported land-surface fluxes in shallow-water-table
environments.

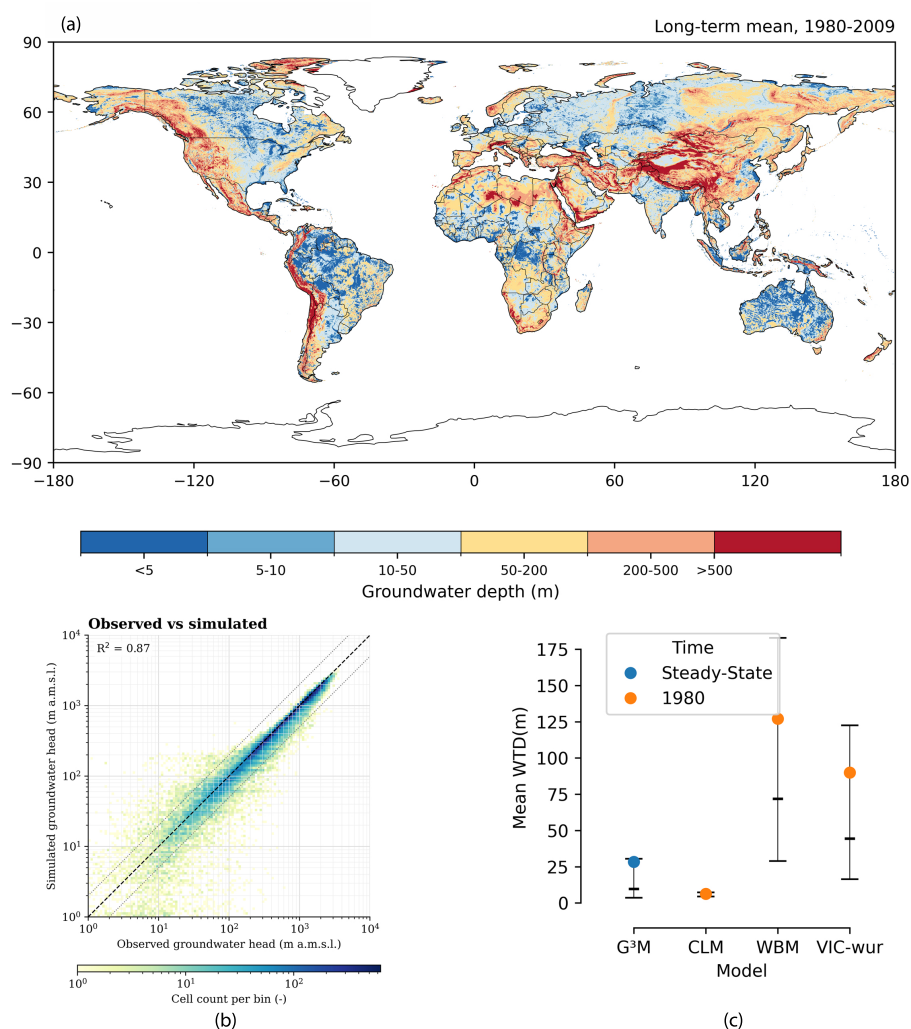


Figure 4. Water table depth evaluation for the VIC-WUR-MODFLOW simulation under natural conditions. **(a)** Long-term mean water table depth for 1980–2009, expressed in meters below land surface. **(b)** Comparison between simulated water tables and reference head datasets. **(c)** Intermodel comparison of global water table depth statistics, including VIC-WUR and models from the ISIMIP Groundwater Sector and related global groundwater modelling studies.

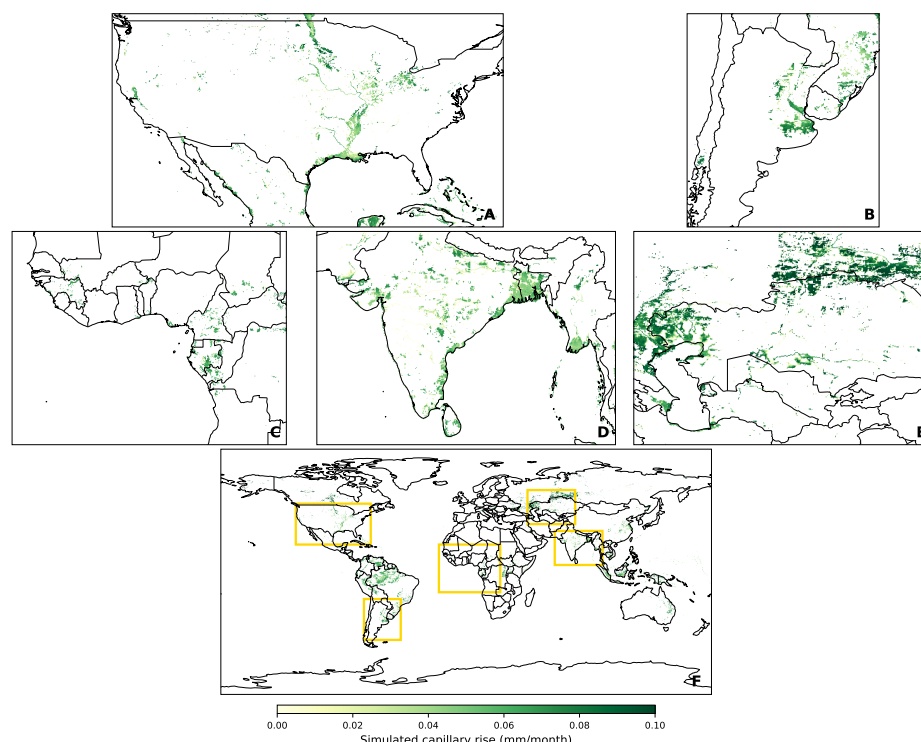


Figure 5. Spatial distribution of simulated long-term mean capillary rise in the coupled simulation. The main panel shows the global pattern, highlighting that capillary rise is spatially concentrated in regions with shallow groundwater. The sub panels (A–E) present selected hotspot regions, including North America, South America, West/Central Africa, parts of the Indian subcontinent and Central Asia, where elevated capillary rise is observed. Values are expressed in mm month^{-1} .

4.4 River discharge and groundwater–surface water interactions

The coupled simulation reproduces the broad magnitude and seasonality of river discharge across the selected GRDC stations (Fig. 6). Relative to the uncoupled configuration, the coupled simulation generally improves seasonal discharge dynamics. This is particularly evident during dry periods, when the coupled configuration outperforms the uncoupled simulation at 70.5% of stations and often produces higher discharge, reflecting the role of groundwater in sustaining river flow under water-limited conditions. Improvements are also evident during the wet season, when the coupled configuration outperforms the uncoupled simulation at 81.6% of stations. Monthly skill diagnostics further show that the largest gains occur between July and September, indicating that groundwater feedbacks are especially important during periods of strong seasonal hydrological forcing. More details can be found in Appendix B1.

Surface water–groundwater exchange is dominated by groundwater discharge to the river network across much of the simulated domain (Fig. 7a). Positive exchange fluxes, representing gaining conditions, are widespread, whereas negative fluxes

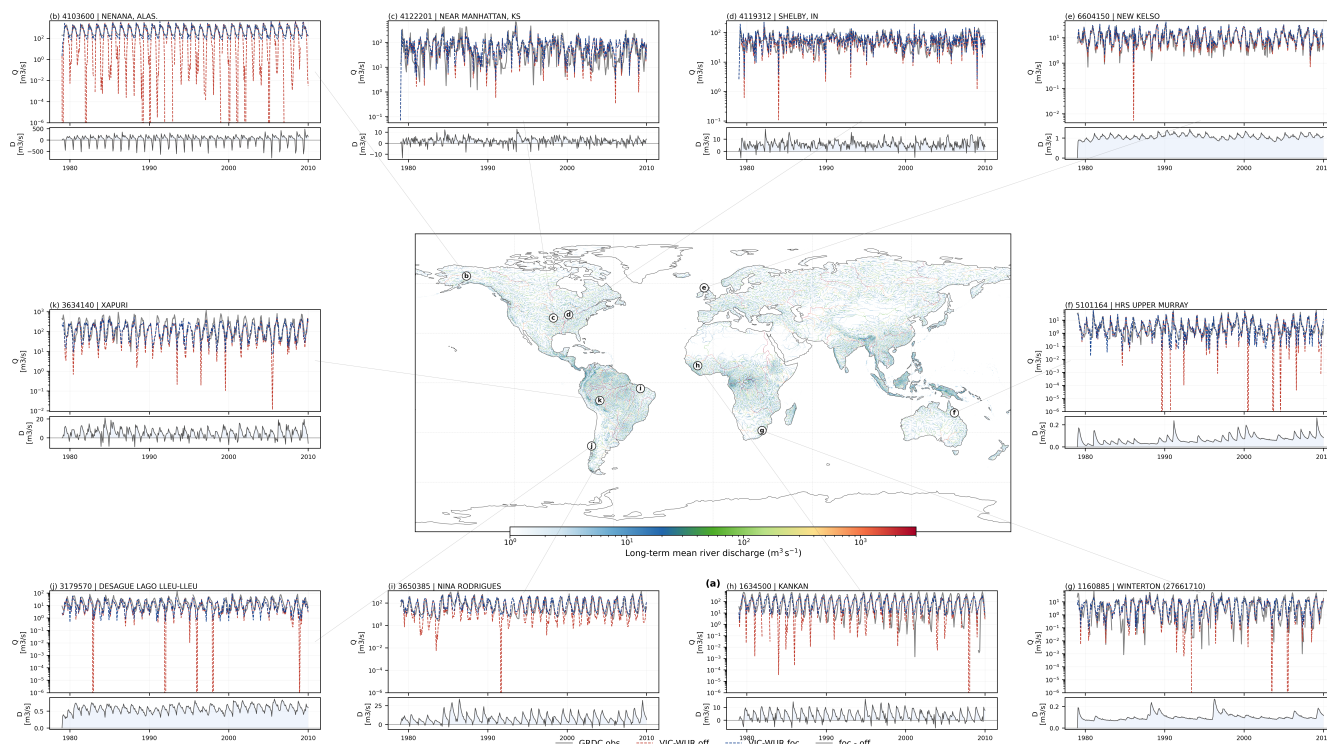


Figure 6. Evaluation of simulated river discharge against GRDC observations at selected stations. The central map shows long-term mean river discharge, and the station markers indicate the basins used for detailed comparison. The surrounding panels show monthly discharge time series for GRDC observations, the uncoupled and coupled VIC-WUR simulations, together with the difference between the coupled and uncoupled simulations (coupled – uncoupled).

indicating river leakage to the aquifer are spatially much more limited. This large-scale pattern is consistent with the expectation that groundwater sustains river flow in humid and groundwater-connected regions.

Baseflow emerges as a key mechanism sustaining streamflow, particularly in humid and groundwater-connected regions (Fig. 7). As shown in Fig. 7b, groundwater support constitutes a substantial fraction of total discharge in many regions under mean annual conditions. Under low-flow conditions (Q10), this role becomes even more pronounced: the Q10 groundwater support ratio, defined here for months with river discharge below the cell-wise Q10 threshold, is significantly higher than the long-term mean groundwater support ratio (Fig. 7c compared to Fig. 7b). This indicates that groundwater contributions become relatively more important as discharge declines, highlighting the role of baseflow in sustaining river flow during dry periods.

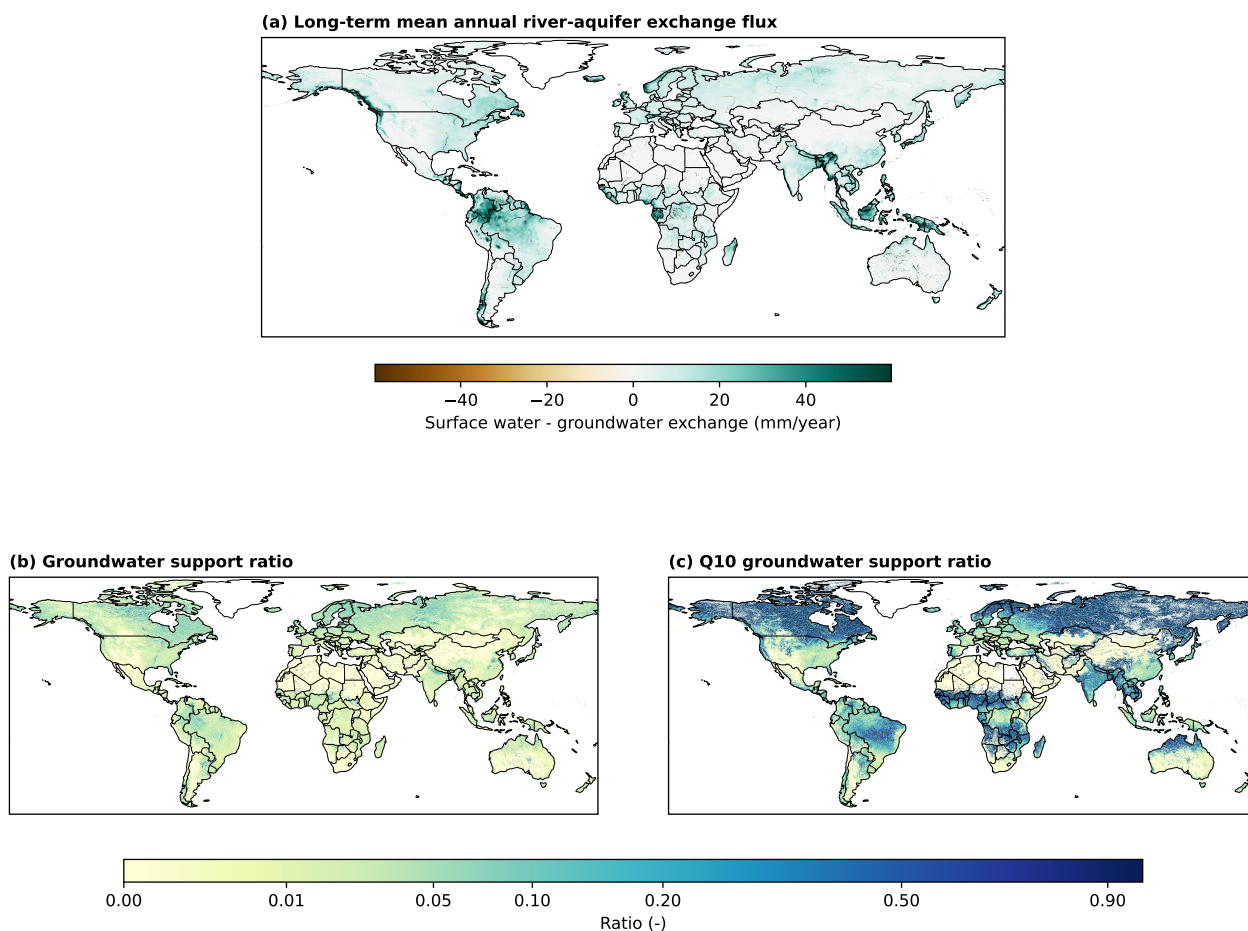


Figure 7. Groundwater–surface water exchange and groundwater-supported discharge in the coupled VIC-WUR simulation. **(a)** Long-term mean annual river–groundwater exchange flux for the common analysis period, expressed in mm yr^{-1} ; positive values indicate groundwater discharge to the river network (gaining conditions), whereas negative values indicate river leakage to the aquifer (losing conditions). **(b)** Groundwater support ratio, defined as the long-term mean positive exchange flux divided by the long-term mean total discharge. **(c)** Q10 groundwater support ratio, calculated in the same way as panel (b) but restricted to months with climatological discharge below the cell-wise Q10 threshold.



5 Discussion

5.1 Global patterns of groundwater recharge, water table depth, and capillary rise

The simulated recharge fields display coherent large-scale patterns that are consistent with established climatic gradients. Recharge broadly follows the spatial distribution of precipitation and evapotranspiration, with high values in humid tropical and monsoon-influenced regions and much lower values in arid and semi-arid zones. This large-scale behaviour is physically plausible and indicates that the coupled model captures the first-order partitioning of water between evapotranspiration, runoff, and subsurface recharge.

At the same time, the magnitude of simulated recharge remains uncertain. Relative to other global groundwater models, VIC-WUR v3.0 tends to produce comparatively high recharge, and comparisons with the external recharge products of Berghuijs et al. (2022) and Moeck et al. (2020) indicate that the model generally lies toward the upper part of the reported range. This tendency suggests that VIC-WUR may overestimate recharge in some regions, while also highlighting the substantial uncertainty that still surrounds global recharge estimation and the influence of forcing, soil, and groundwater parameter data.

The comparatively higher groundwater recharge simulated by VIC-WUR v3.0 can be partly attributed to the explicit and dynamically constrained representation of capillary rise. By sustaining root-zone soil moisture during dry periods, capillary rise stabilises soil-groundwater interactions and alters the temporal structure of infiltration and percolation, which can result in higher time-averaged recharge than in global assessments that neglect or simplify groundwater-soil feedbacks.

These recharge patterns propagate into the simulated groundwater system and help explain the broad distribution of water table depth. Shallow water tables occur mainly in deltas, floodplains, and humid lowlands, whereas deeper water tables are more common in mountainous and arid regions. This large-scale behaviour reflects the combined influence of recharge, topography, aquifer properties, and river-network connectivity on groundwater storage and drainage. Differences from other global groundwater modelling studies are therefore expected, particularly where recharge magnitude, aquifer parameterisation, or the representation of river-aquifer exchange differ.

Capillary rise, although much smaller in magnitude than recharge at the global scale, emerges as an important process in regions with shallow groundwater. In these regions, upward groundwater flux can support soil moisture and evapotranspiration, especially during dry periods. This result underlines the value of explicitly representing capillary rise in global models.

5.2 Dominant controls on simulated groundwater dynamics

Following earlier global groundwater modelling studies (e.g., Berghuijs et al. (2022); de Graaf et al. (2017); He et al. (2025); Sutanudjaja et al. (2018)), our sensitivity analysis focused on saturated hydraulic conductivity (K_{sat}) as the dominant parameter influencing water table depths and groundwater dynamics. We tested the sensitivity of the model to variations in K_{sat} by factors of 0.1, 1, and 10. As expected, higher conductivities produced lower and more spatially uniform water tables, along with stronger exchange fluxes between groundwater and surface water. Conversely, lower conductivities led to steeper hydraulic gradients and reduced interactions with surface systems (Marinelli et al., 2025).



Additional tests explored variations in soil parameters, recharge estimates, and river conductance. These factors had comparatively minor effects. The limited effects of variations in recharge, for example, reflect its relatively smaller influence than that of variations in hydraulic conductivity. Drainage processes further dampen sensitivity: increases in recharge raise the water table, steepen hydraulic gradients, enhance drainage, and subsequently lower the water table again, creating a positive feedback loop. Similarly, variations in river conductance produced only modest changes in groundwater–surface water exchange (Marinelli et al., 2025).

Overall, simulated water tables varied by approximately -20% to $+20\%$ across parameter settings. The largest deviations occurred in regions with high transmissivity and low recharge, such as the Sahara and Australian deserts, where groundwater has a higher propensity to disconnect from local drainage systems. Substantial variations also appeared in areas with high transmissivity and shallow water tables, including the Amazon and Indus basins, where groundwater remains strongly connected to surface drainage networks.

5.3 Major sources of uncertainty in the coupled modelling framework

Several sources of uncertainty influence the interpretation of the presented results. First, hydrogeological simplifications remain unavoidable in global-scale modelling, because generic subsurface parameterisation cannot fully represent local heterogeneity in aquifer geometry and hydraulic properties. Second, uncertainties in forcing data, particularly precipitation, directly affect simulated recharge and water table depth. Third, the representation of topography and river networks introduces additional uncertainty, as the coarse resolution and aggregation of digital elevation data can alter drainage connectivity and groundwater–surface water exchange. Missing human influences, including groundwater abstraction, irrigation return flows, and reservoir regulation, further contribute to discrepancies with observations in intensively managed regions. Coupling limitations also remain important: the current sequential exchange between VIC-WUR and MODFLOW may overestimate river leakage and does not fully capture short-term feedbacks between the land surface and groundwater system. Finally, the coarse spatial resolution limits the model’s ability to resolve fine-scale gradients that are important for recharge processes and stream–aquifer interactions.

Despite these uncertainties, the coupled VIC-WUR v3.0 framework provides a physically consistent and internally coherent representation of groundwater–surface water interactions that is well suited for large-scale comparative analyses and sensitivity studies. This makes it a useful platform for exploring the implications of groundwater dynamics for water availability under changing climate and land-use conditions, as discussed in the following section.

5.4 Broader interpretation and pathways forward

From a broader perspective, these findings help clarify how groundwater systems respond to climatic variability and long-term change. The results highlight the importance of representing surface–groundwater connectivity in a physically consistent way, as this connection shapes groundwater sustainability, the resilience of river systems, and the capacity of landscapes to buffer hydrological extremes. In this sense, the VIC-WUR framework moves beyond static global groundwater mapping toward a dynamic, process-based understanding of groundwater behaviour.



A key pathway forward is to move from the current monthly sequential coupling toward tighter and more frequent exchange between the land-surface and groundwater components. Early experiments—particularly in the Indus Basin—already show that water tables evolve differently when baseflow and capillary fluxes are dynamically fed back into VIC-WUR. These initial results underscore the value of integrated modelling frameworks that capture the full spectrum of interactions among climate, surface water, and groundwater. Such coupling will be essential for assessing how groundwater responds to droughts, how much buffering capacity aquifers provide, and how land surface processes shift when groundwater becomes stressed.

Progress toward tighter coupling also depends on several technical improvements. The current coupling scheme between VIC-WUR and MODFLOW introduces performance bottlenecks, especially during repeated re-initialization steps. Streamlining this interface—through more efficient data handling, reduced precision state storage, and improved I/O throughput—will allow groundwater states and fluxes to be exchanged more frequently and at lower computational cost. These developments are not merely engineering refinements: they directly support more realistic simulation of processes such as capillary rise, baseflow generation, and groundwater–surface water feedbacks under transient conditions.

Equally important is the explicit inclusion of human water use. Groundwater abstraction, irrigation return flows, and reservoir operations fundamentally reshape hydrological connectivity in many regions. Incorporating these processes will allow the model to address questions related to groundwater depletion, irrigation sustainability, and the redistribution of water under competing demands. Embedding human influences within the modelling framework is therefore a natural next step toward evaluating future water resource trajectories. Capillary rise illustrates why tighter coupling matters. Although globally smaller than recharge, it plays a disproportionate role in regions with shallow groundwater, sustaining evapotranspiration and buffering vegetation during dry periods. Its influence becomes even more pronounced under climate extremes or groundwater decline. Representing this process dynamically will be important for capturing land–atmosphere feedbacks and for assessing how ecosystems respond when water tables fall.

Together, these developments point toward a next generation of global groundwater modelling—one that is physically grounded, dynamically coupled, and capable of representing both natural and human-driven processes.

6 Conclusion

This study presents VIC-WUR v3.0, a new global hydrological modelling framework in which the land-surface model VIC-WUR is coupled with the physically based groundwater flow model MODFLOW 6. Compared with the previous groundwater representation in VIC-WUR, the new framework explicitly simulates transient groundwater flow, water tables, groundwater–river exchange, and groundwater-depth-dependent capillary rise. In this way, VIC-WUR v3.0 provides a more physically based representation of groundwater—surface water interactions at the global scale.

The simulated groundwater patterns are broadly consistent with previous large-scale hydrological and groundwater modelling studies, although VIC-WUR v3.0 tends to simulate comparatively higher groundwater recharge within the existing global model estimates. The results further show that capillary rise is not a diffuse background flux, but a spatially concentrated process that is especially relevant in regions with shallow groundwater, where it can support soil moisture and evapotranspiration.



400 At the same time, the results remain subject to uncertainties related to hydrogeological parameterisation, forcing data, river network representation, coupling frequency, and the omission of human water use. These limitations point to clear priorities for future model development. In particular, tighter coupling between the land surface and groundwater components, together with explicit representation of groundwater abstraction, irrigation return flows, and reservoir operations, will be essential for improving realism and expanding the applicability of the framework. Further technical optimization of the VIC-WUR–MODFLOW interface will also support more frequent and computationally efficient coupling. Overall, VIC-WUR v3.0 provides a new platform for investigating groundwater–surface water interactions and future water availability under climate change, land-use change, and human impacts.

Code and data availability. The frozen version of the VIC-WUR v3.0 coupling code used in this study is publicly available on Zenodo: <https://doi.org/10.5281/zenodo.20752995> (Liu et al., 2026)

410 **Appendix A: Model configuration, parameterisation and input data**

A1 Groundwater model configuration, parameters and boundary conditions

This section provides supplementary information on the configuration of the MODFLOW groundwater model used in the coupled VIC-WUR v3.0 framework. It summarizes the large-scale boundary conditions and the main hydrogeological parameter fields. Fig. A1 shows the imposed boundary conditions, including the representation of the river network. While Fig. A2 presents the hydraulic property fields used in the model, such as aquifer thickness and hydraulic conductivity.

415 Along the coastline, constant-head (CHD) boundary conditions are imposed at sea level to represent the hydraulic connection between the groundwater system and the ocean. Surface water–groundwater interactions are represented following the large-scale modelling approach of de Graaf et al. (2017). Large rivers are implemented with the MODFLOW RIV package, which allows bidirectional exchange between the river and the aquifer as a function of river stage, river bottom elevation, and water table. Smaller rivers and local drainage features are represented with the DRN package, which only allows water to leave the groundwater system. Together, the RIV and DRN packages provide a large-scale representation of both river–aquifer exchange and local groundwater drainage within the coupled model framework.

For large rivers (river width larger than 10 m) represented by the RIV package, the exchange flux depends on the relative position of water table and river stage, following de Graaf et al. (2017):

$$425 \quad Q_{\text{riv}} = \begin{cases} c(H_{\text{RIV}} - h), & h > R_{\text{BOT}}, \\ c(H_{\text{RIV}} - R_{\text{BOT}}), & h \leq R_{\text{BOT}}, \end{cases} \quad (\text{A1})$$

where Q_{riv} is the river–aquifer exchange flux, c is the river-bed conductance, H_{RIV} is the river stage, h is the water table, and R_{BOT} is the river bottom elevation. This formulation allows bidirectional exchange between the river and the aquifer.



When water table is below river stage, water infiltrates from the river into the aquifer; when water table is above river stage, groundwater discharges to the river.

430 For smaller rivers (river width smaller than 10 m) and local drainage features represented by the DRN package, flow is only allowed from the aquifer to the drainage network. In the present implementation, the drain elevation is defined by the floodplain elevation, so that drainage occurs when water tables rise above the local floodplain level:

$$Q_{\text{drn}} = \begin{cases} c(H_{\text{DRN}} - h), & h > H_{\text{DRN}}, \\ 0, & h \leq H_{\text{DRN}}, \end{cases} \quad (\text{A2})$$

where Q_{drn} is the drainage flux, c is the drain conductance, and H_{DRN} is the floodplain elevation used as the drain elevation
435 in the model. This formulation represents one-way drainage from groundwater to smaller channels and local drainage features. River and drain conductances were prescribed following the same large-scale parameterisation as in de Graaf et al. (2017).

The hydraulic property fields shown in Fig. A2 follow the global aquifer parameterisation of de Graaf et al. (2017), which combines lithology-based permeability estimates, terrain-based aquifer thickness estimates, and storage properties assigned by hydrogeological class. In the present model setup, these spatially distributed parameter fields are prescribed as static inputs to
440 the MODFLOW model and remain fixed during the transient simulations, while recharge and river forcing vary over time.

A2 Groundwater recharge formulation at the lower boundary of the VIC-WUR soil column

In VIC-WUR, vertical water movement through the soil column is represented as a sequence of downward drainage fluxes between adjacent soil layers during each runoff sub-step. Under the standard configuration, these fluxes redistribute soil moisture within the three-layer soil column and determine the drainage leaving the upper layers. In the groundwater-coupled configuration (GWM = TRUE), this concept is extended by adding an extra lower boundary beneath the third soil layer, so that drainage
445 from the deepest soil layer can be passed to the groundwater model as recharge.

As a result, four downward drainage fluxes are evaluated during each runoff sub-step. The first three represent drainage within the soil column, whereas the fourth represents drainage from the lowest soil layer to the aquifer. In the model output, OUT_GWRECHARGE corresponds to drainage from the third soil layer into the groundwater system.

450 For each soil layer, the downward drainage flux is calculated from the liquid water content remaining after evaporation has been removed. If the available liquid water in layer i is denoted by W_i^* , the residual water storage by $W_{r,i}$, the maximum water storage by $W_{\text{max},i}$, the saturated hydraulic conductivity by $K_{s,i}$, and the Brooks–Corey exponent by b_i , the provisional downward drainage flux is calculated as

$$Q_{\text{down},i} = \begin{cases} W_i^* - \left[(W_i^* - W_{r,i})^{1-b_i} - \frac{(1-b_i)K_{s,i}\Delta t}{(W_{\text{max},i} - W_{r,i})^{b_i}} \right]^{\frac{1}{1-b_i}} - W_{r,i}, & W_i^* > W_{r,i}, \\ 0, & W_i^* \leq W_{r,i}, \end{cases} \quad (\text{A3})$$

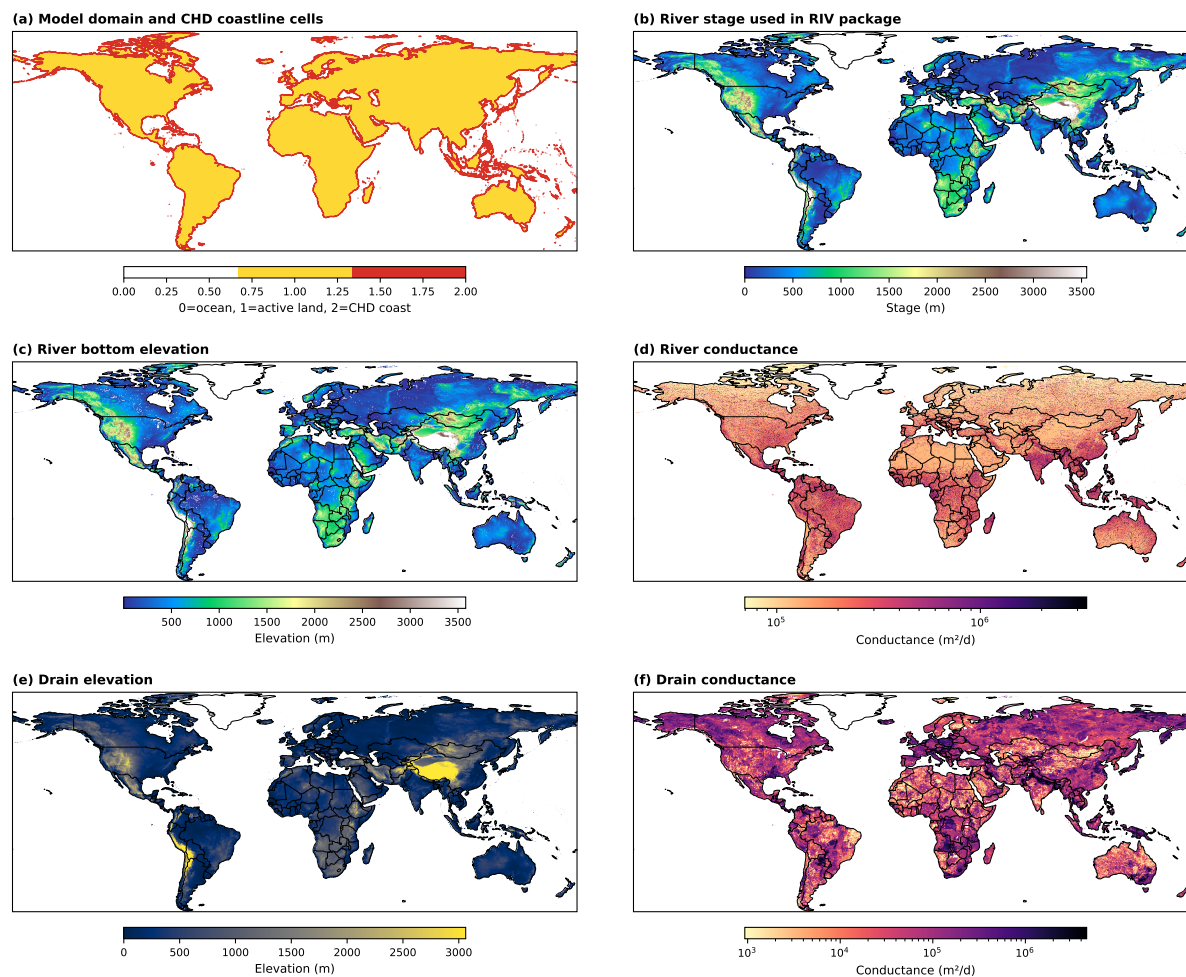


Figure A1. Steady-state boundary conditions used in the MODFLOW groundwater model. The panels show (a) the model domain and constant-head (CHD) coastline cells, (b) river stage used in the RIV package, (c) river bottom elevation, (d) river conductance, (e) drain elevation, and (f) drain conductance. These boundary conditions define the large-scale groundwater and groundwater–surface water exchange framework prior to the transient simulations.

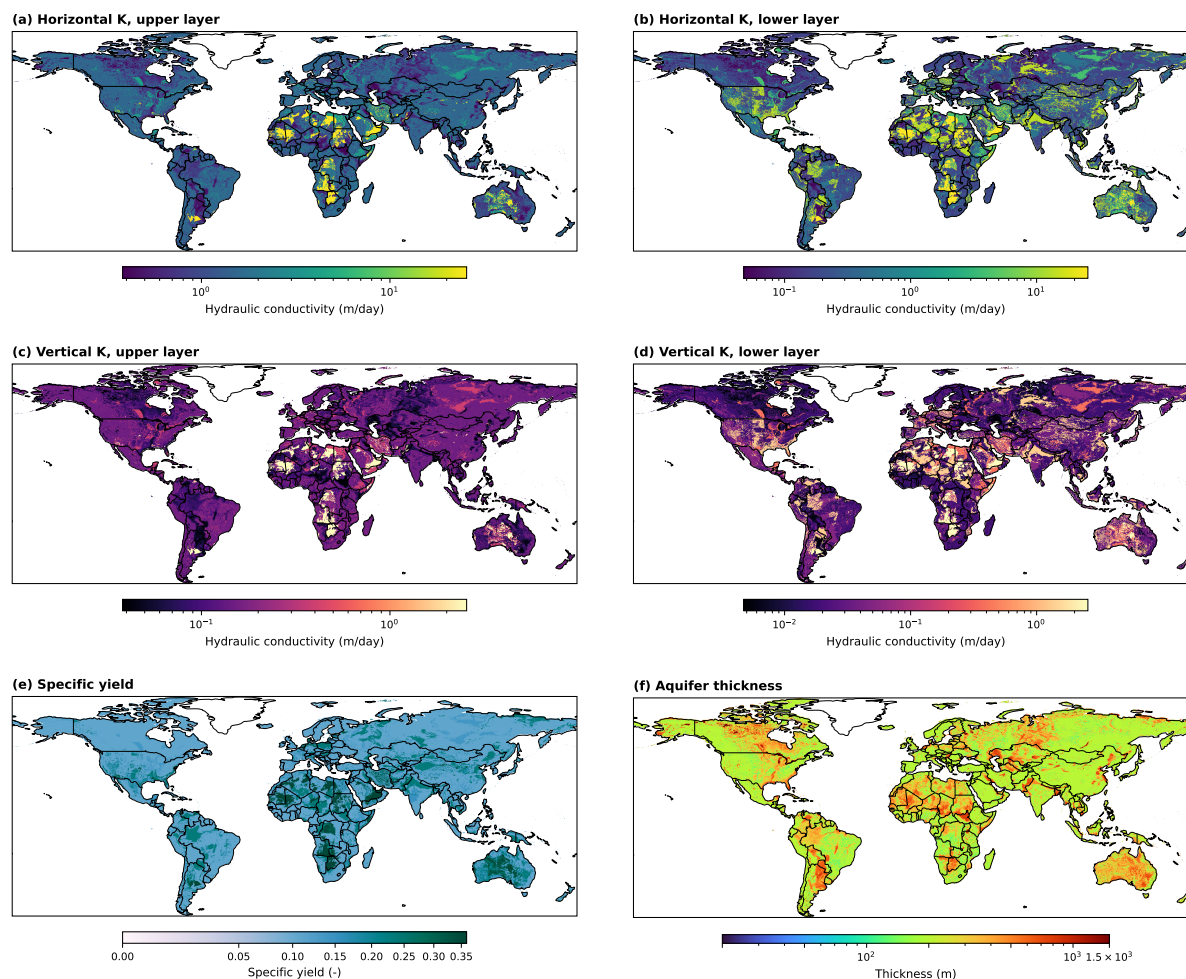


Figure A2. Hydrogeological parameters used in the MODFLOW groundwater model. The panels show (a) horizontal hydraulic conductivity in the upper layer, (b) horizontal hydraulic conductivity in the lower layer, (c) vertical hydraulic conductivity in the upper layer, (d) vertical hydraulic conductivity in the lower layer, (e) specific yield, and (f) aquifer thickness. These spatially distributed properties define the large-scale hydraulic behaviour of the groundwater system.



455 where $K_{s,i}^{\Delta t}$ is the saturated hydraulic conductivity converted to the runoff sub-step. This formulation describes the amount of water that can drain downward from a given soil layer during one runoff sub-step, subject to the hydraulic properties and storage limits of that layer.

After this provisional drainage is diagnosed, soil moisture is updated sequentially from the top layer downward while enforcing the residual and maximum storage limits of each layer. Any excess moisture is redistributed upward and, if necessary,
460 added to surface runoff. In the groundwater-coupled configuration, the deepest drainage flux is then taken as the groundwater recharge flux. The recharge passed from VIC-WUR to the groundwater model is therefore the final, storage-constrained drainage across the lower boundary of the third soil layer, accumulated over all runoff sub-steps and weighted by frost-area fractions:

$$R_{\text{gw}} = \sum_f \alpha_f \sum_k Q_{\text{down},4,f}^{(k)}, \quad (\text{A4})$$

465 where α_f is the fractional area of frost sub-area f . This quantity is written to OUT_GWRECHARGE. This formulation therefore defines groundwater recharge in VIC-WUR as the final, storage-constrained drainage leaving the lowest soil layer, providing the flux that is passed to the groundwater model in the coupled framework.

A3 Parameterization of groundwater-depth-dependent capillary rise

The groundwater-depth-dependent capillary rise formulation requires three primary parameters for each active land grid cell:
470 the bottom elevation of the lowest VIC-WUR soil layer (Z_{bot}), the maximum capillary rise height ($h_{c,\text{max}}$), and the maximum capillary rise flux ($q_{c,\text{max}}$). Z_{bot} is obtained directly from the VIC-WUR soil parameterisation as the land-surface elevation minus the total depth of the soil column. $h_{c,\text{max}}$ is calculated following Liu et al. (2014) as:

$$h_{c,\text{max}} = \frac{\sigma n \cos \alpha}{\sqrt{2} \eta \rho_w g K_s} + (1 - n) h_a, \quad (\text{A5})$$

where n is the effective soil porosity [-], K_s is the saturated hydraulic conductivity [m s^{-1}], α is the contact angle between
475 water and soil particles [$^\circ$], and h_a is the air-entry height [m]. The remaining variables are the surface tension of water σ , the viscosity of water η , the density of water ρ_w , and gravitational acceleration g .

The maximum capillary rise flux, $q_{c,\text{max}}$, is calculated using the Gardner–Eagleson approach (Eagleson, 1978):

$$q_{c,\text{max}} = K_s a \left(\frac{|\psi_s|}{GWD} \right)^\beta, \quad (\text{A6})$$

with

$$480 \quad \beta = 2 + \frac{3}{b}, \quad (\text{A7})$$



$$a = 1 + \frac{3}{2(\beta - 1)}, \quad (\text{A8})$$

where K_s is the saturated hydraulic conductivity [m d^{-1}], ψ_s is the saturated matric potential [m], GWD is groundwater depth [m], and b is the Brooks–Corey pore-size distribution index [-]. In practice, the absolute value of saturated matric potential is used to avoid non-physical negative fluxes.

485 The secondary parameters required to derive $h_{c,\max}$ and $q_{c,\max}$ are obtained from a combination of VIC-WUR soil parameters, soil-texture-based pedotransfer information, and literature-based constants. In the present implementation, saturated hydraulic conductivity and porosity are derived from the VIC-WUR soil parameterisation, while the Clapp–Hornberger parameters are assigned by soil texture class using a global soil texture dataset. The contact angle and air-entry height are prescribed from literature values. Together, these parameter fields provide the spatially distributed inputs needed to calculate the primary
490 capillary rise parameters used by the coupled VIC-WUR–MODFLOW framework. These primary parameters are then passed to the MODFLOW EVT-based capillary rise formulation in the coupled VIC-WUR–MODFLOW framework.

Appendix B: Supplementary evaluation and result diagnostics

B1 Seasonal patterns of key hydrological components

This section provides supplementary information on the seasonal patterns of the main hydrological components discussed in
495 Section 4. The figures are intended to complement the annual-mean and long-term results by illustrating the seasonal timing and amplitude of water table depth, groundwater–surface water exchange, and groundwater recharge. Together, they help identify regions with strong seasonal variability and provide additional context for the spatial patterns.

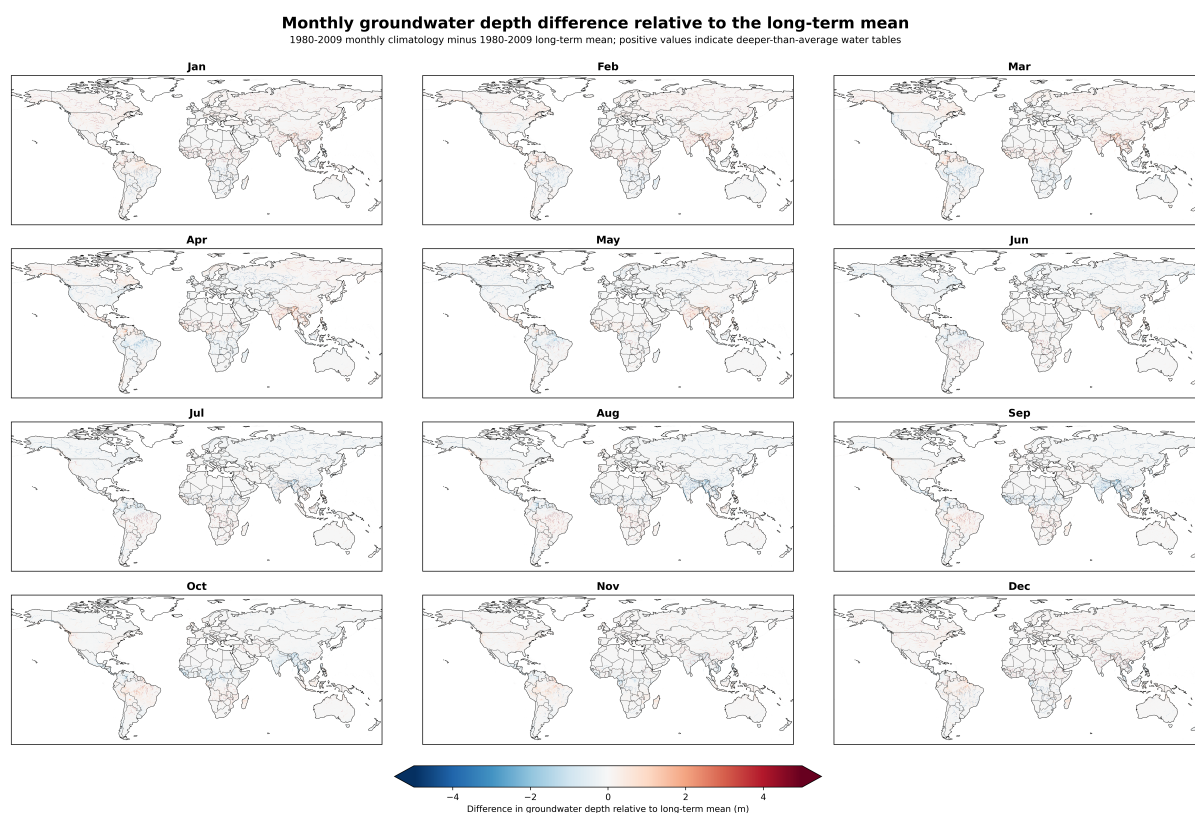


Figure B1. Monthly deviations of water table depth relative to the long-term mean. Positive and negative anomalies indicate periods when groundwater depth is seasonally deeper or shallower than average, respectively, thereby highlighting the timing and spatial distribution of seasonal groundwater storage fluctuations.

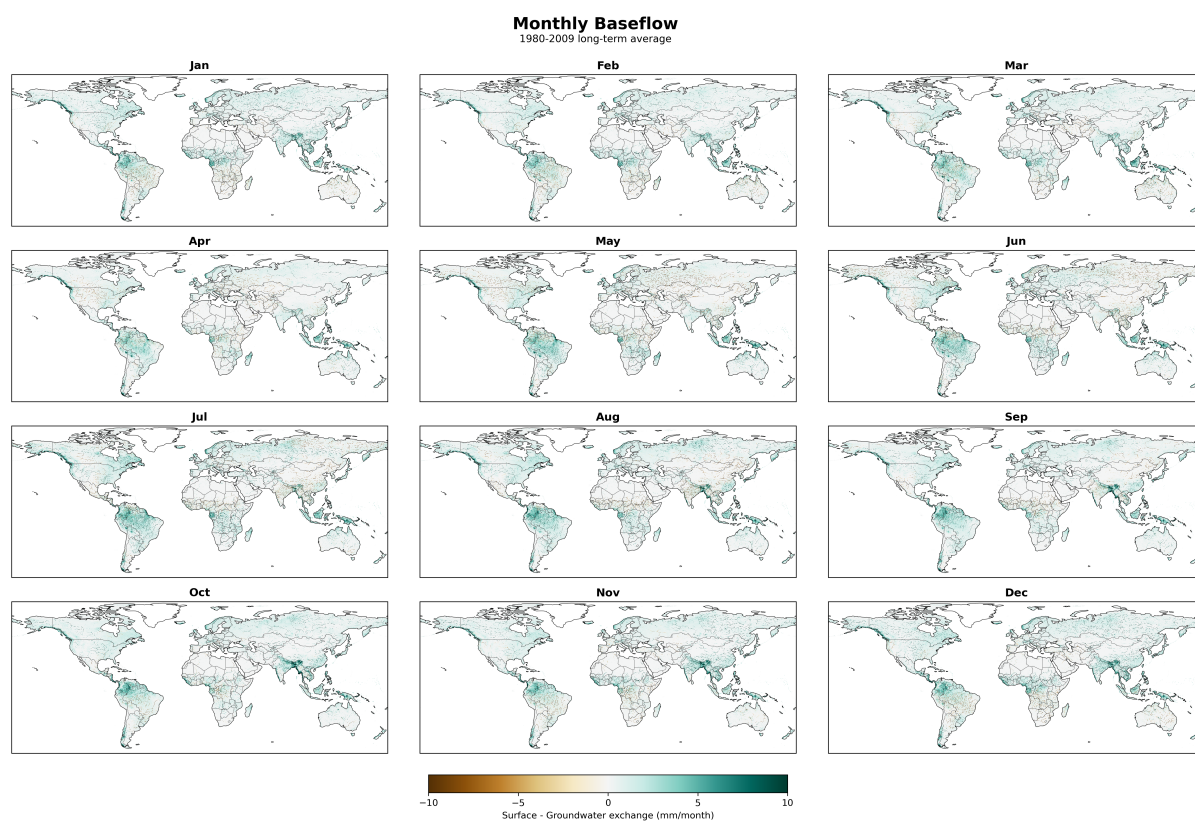


Figure B2. Monthly climatology of groundwater–surface water exchange showing the seasonal evolution of exchange fluxes which helps distinguish regions with persistently gaining conditions from those where the magnitude of exchange varies more strongly over the year.

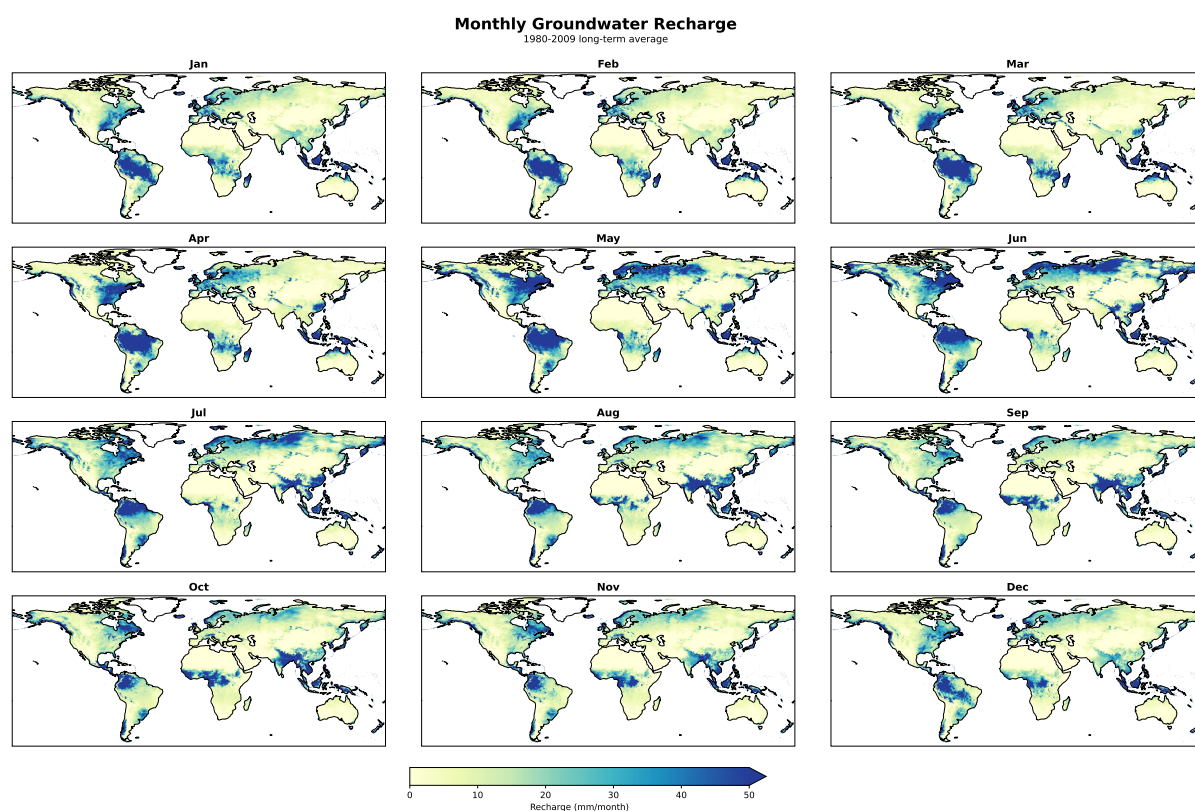


Figure B3. Monthly climatology of groundwater recharge for 1980–2009. Compared with the annual-mean recharge patterns shown in the main text, this figure provides additional detail on the seasonal concentration of recharge and highlights regions where recharge is strongly linked to wet-season precipitation.



B2 Supplementary analysis of groundwater recharge

Fig. B4 compares long-term mean annual groundwater recharge simulated by VIC-WUR with two external reference datasets.

500 Panel (a) shows the comparison against the global gridded recharge product of Berghuijs et al. (2022), using all overlapping valid grid cells, whereas panel (b) compares VIC-WUR with the site-based compilation of Moeck et al. (2020). In both cases, VIC-WUR reproduces the broad first-order variability in recharge, but with substantial scatter and a tendency toward higher values, particularly relative to the Moeck et al. dataset. These comparisons indicate that the simulated recharge patterns are broadly consistent with external products, while also suggesting that VIC-WUR tends to estimate comparatively strong

505 recharge in some regions.

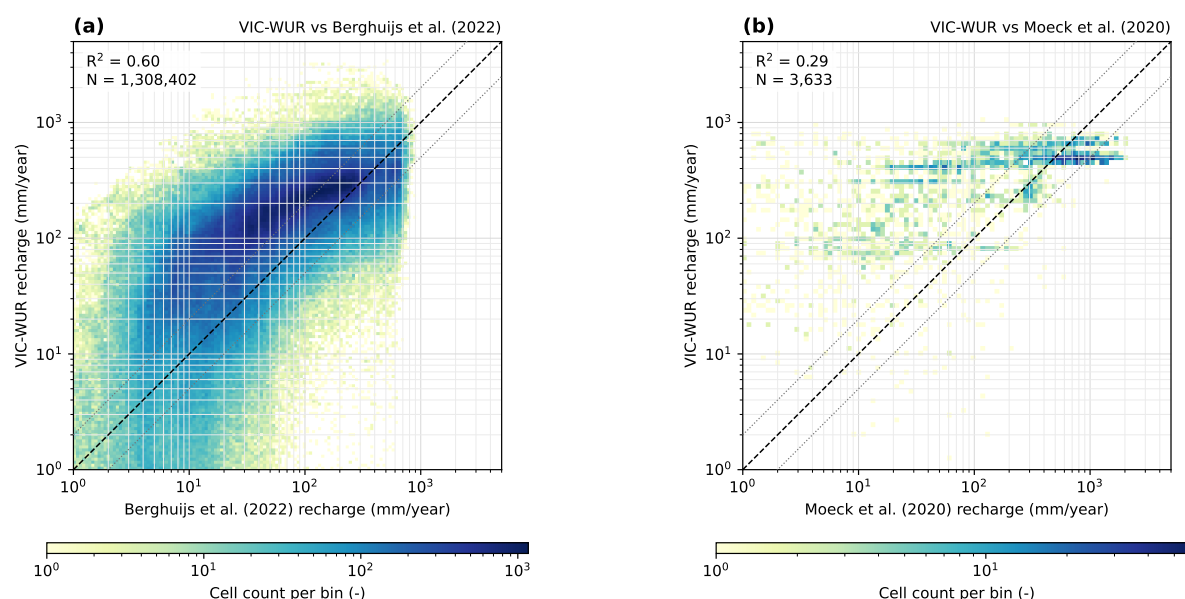


Figure B4. Comparison of long-term mean annual groundwater recharge simulated by VIC-WUR with two datasets. **(a)** Density scatter plot of VIC-WUR recharge against the global gridded recharge product of Berghuijs et al. (2022), using all overlapping valid grid cells. **(b)** Density scatter plot of VIC-WUR recharge against the site-based recharge compilation of Moeck et al. (2020). In both panels, colour indicates the number of cells or sites within each bin, and the dashed lines denote the 1:1, 2:1, and 1:2 relationships.



B3 Supplementary evaluation of water tables

This section presents additional analysis of simulated water table performance relative to observation-based datasets. The first figure evaluates the relationship between water table residual and long-term mean water table depth, while the second figure examines the simulated–observed agreement across Köppen–Geiger climate classes (Beck et al., 2018). These plots provide
510 additional context for the large-scale water table evaluation discussed in the main text.

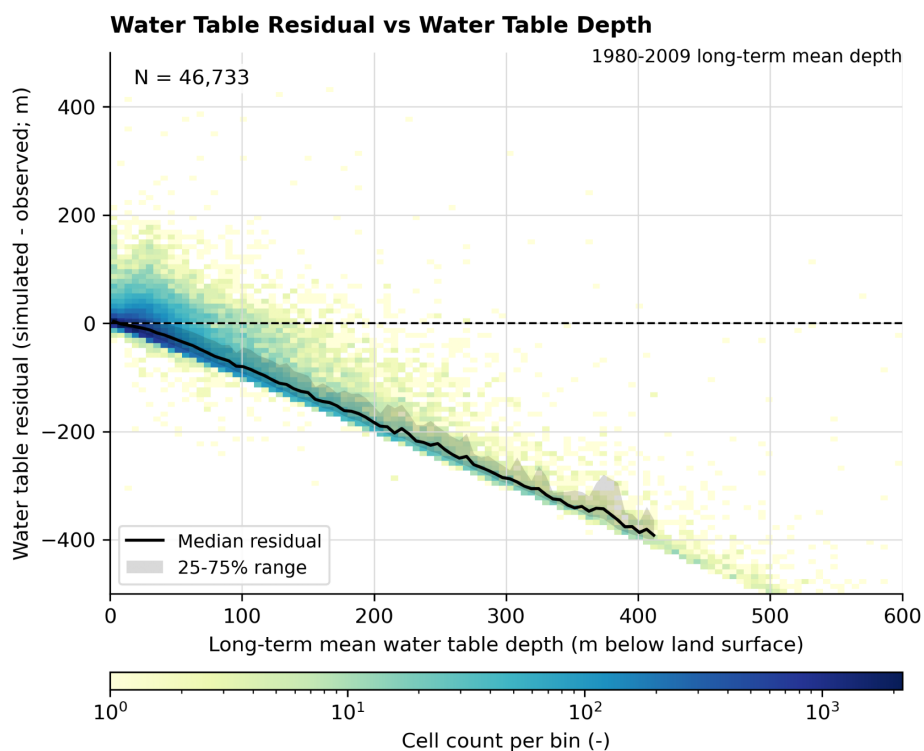


Figure B5. Relationship between water table residual and long-term mean water table depth. The background shading shows the number of cells per bin, the black line indicates the median residual, and the shaded envelope shows the interquartile range (25 %–75 %). Residuals are defined as simulated minus observed water table.

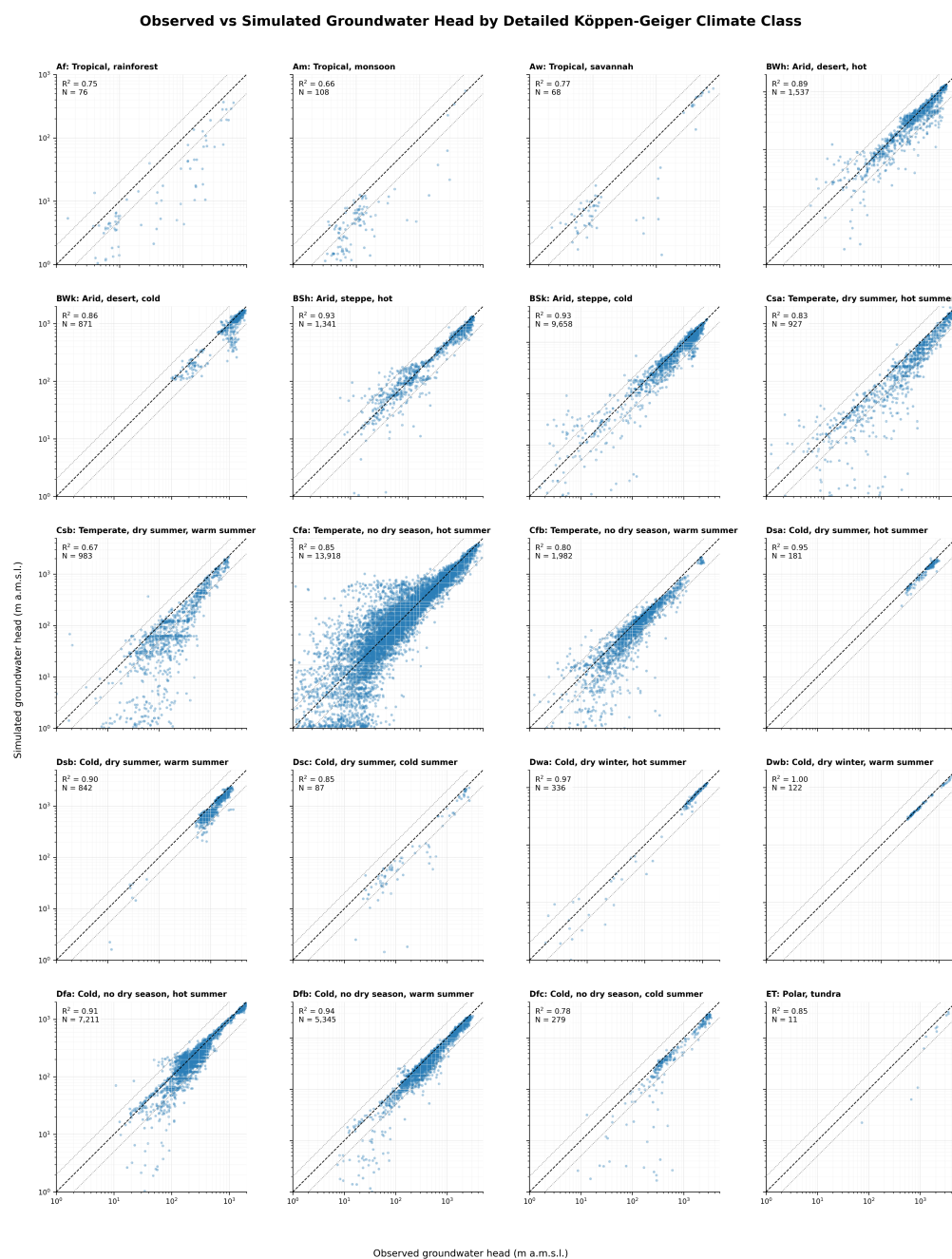


Figure B6. Comparison between simulated and observed water table across detailed Köppen–Geiger climate classes. Each panel shows a log–log scatter plot for one climate class. The dashed and dotted reference lines indicate the 1:1, 2:1, and 1:2 relationships, respectively.



Author contributions. SL and IdG developed the VIC-WUR–MODFLOW coupling framework. SL and LN prepared the input datasets. SL, LN, and EB developed the parameterisation. HY carried out the pilot study and analysed the results. FK, KD, and IdG contributed to the interpretation of the results and the development of the modelling framework. SL, KD, and IdG wrote the original draft of the manuscript. IdG supervised the study. All authors reviewed and edited the manuscript.

515 *Competing interests.* The authors declare that they have no conflict of interest.

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