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Global projections of groundwater sustainability through the end of the century

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Abstract. Groundwater is an essential freshwater resource for sustaining groundwater-dependent ecosystems, maintaining streamflow during low-flow periods, and meeting anthropogenic water demands. With increasing pressures from climate change and water use expected to intensify groundwater stress throughout the 21st century, it is valuable to evaluate the temporal evolution of projected groundwater sustainability. Here, we project global groundwater sustainability from 2026-2100 using a newly coupled VIC-WUR-MODFLOW modelling framework forced with bias-adjusted climate projections and future water use scenarios under SSP1-2.6 and SSP3-7.0. Using an environmental flow-based approach, we calculated monthly groundwater sustainability thresholds based on *natural* conditions. We compared simulated output of groundwater head under *human-impacted* conditions to these thresholds to quantify the frequency, severity, timing, and duration of unsustainable groundwater use at 5-arcmin spatial resolution. Our results project groundwater head to drop below environmentally sustainable thresholds at least once from 2026-2100 in ~90% of evaluated gridcells, demonstrating that unsustainable groundwater use, leading to harmful ecosystem impacts, is likely to be widespread throughout the 21st century. Despite its spatial prolificness, groundwater unsustainability is primarily characterized by recurring violations rather than permanent threshold exceedances. Global medians of frequency and longest continuous duration of unsustainable conditions are 30% and 40 months respectively. The most severe violations of sustainable conditions are concentrated within a limited number of hotspot regions, including the Indo-Gangetic Plain, North China Plain, Central Valley, and High Plains. Distinct seasonal patterns also emerge across many aquifers, and unsustainable conditions generally increase during the late-century (2076-2100). Between SSP1-2.6 and SSP3-7.0, the main difference in our findings is in projections of unsustainable severity, indicating that future climate and socioeconomic pathways may primarily influence the degree to which groundwater systems drop below environmentally sustainable conditions rather than whether these thresholds are exceeded. By explicitly resolving seasonal, inter-annual, and decadal dynamics of global groundwater sustainability, this study provides a global-scale framework for identifying future hotspots of groundwater overexploitation which could guide groundwater management strategies aimed at supporting environmental, hydrogeological, and anthropogenic water demands.

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1 Introduction

Groundwater comprises the largest share of accessible freshwater for humans and the environment (Gleick, 1993). This resource plays a critical role in supporting groundwater-dependent ecosystems (Rohde et al., 2024), supplying water of sufficient quantity (de Graaf et al., 2019; Gleeson and Richter, 2018; Marinelli et al., 2024) and quality (van Vliet et al., 2023) to wetlands and surface water bodies, protecting coastal aquifers from salinization (Konikow and Kendy, 2005), and providing freshwater to meet anthropogenic demands (Wada et al., 2014). During droughts and low-flow periods, groundwater becomes increasingly important for sustaining streamflow and aquatic ecosystems (Mohan et al., 2023). Largely driven by anthropogenic climate change, population growth, and economic development, the pressure on groundwater resources to meet these global environmental and anthropogenic demands is increasing (Steffen et al., 2015; Vörösmarty et al., 2010). These demands largely come from irrigated agriculture, as irrigation is the water use sector with the largest reliance on groundwater resources (Wada et al., 2012). In turn, the state of groundwater systems can reach unsustainable conditions due to overexploitation (e.g., de Graaf et al., 2019; Scanlon et al., 2023), negatively impacting the natural environment (Famiglietti, 2014; Konikow and Kendy, 2005; Rohde et al., 2024). Although groundwater management decisions are typically made at regional and local scales, a comprehensive global assessment of projected groundwater sustainability helps to identify emerging hotspots of risk, reveal large-scale patterns, and provide context for regional planning efforts. Moreover, groundwater systems often have slow response times to climatic and anthropogenic stresses, meaning shifts in water management practices made in the short-term may have long-lasting consequences for future groundwater conditions.

A recent global assessment (Marinelli et al., 2025) was the first to quantify groundwater sustainability at the global-scale for the historic period (1984-2018), providing new insights into the degree of sustainable and unsustainable groundwater use that has already occurred. Similarly, de Graaf et al. (2019) extended a groundwater sustainability assessment into the future by providing the first global-scale projections of when environmental sustainability limits may be exceeded for the first time due to groundwater pumping through 2100. Together, these studies assessed crossings of historic and future sustainability thresholds, but did not evaluate how groundwater sustainability evolves beyond threshold exceedance. As a result, key characteristics of future groundwater unsustainability (e.g., frequency, severity, timing, duration), which are critical for assessing the risk and long-term consequences of groundwater overexploitation, remain largely unexplored at the global scale. Here, we extend the historic groundwater sustainability assessment of Marinelli et al. (2025) through 2100 at discretized timesteps and complement the threshold-based environmental flow assessment of de Graaf et al. (2019) with explicit evaluations of groundwater sustainability dynamics beyond initial exceedances. We use model output at 5-arcmin spatial resolution and monthly temporal resolution to quantify the recurrence, persistence, seasonality, and severity of groundwater unsustainability.

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To evaluate how groundwater sustainability evolves beyond the initial crossing of sustainability thresholds, we projected groundwater sustainability through 2100 using the recently developed coupled global hydrological-groundwater modelling framework VIC-WUR-MODFLOW (Liu et al., 2026) forced with climate and water use projections (ISIMIP, 2026b; Lange and Büchner, 2021). By applying a similar analysis as the historic assessment, we assessed the evolution of groundwater sustainability through 2100, identified emerging hotspots of groundwater overexploitation, and evaluated where groundwater sustainability is projected to improve. Using monthly simulations of groundwater head and groundwater discharge, we calculated spatially and temporally dynamic groundwater sustainability thresholds derived from an environmental flow perspective, considering low-flow conditions in connected groundwater-surface water systems, following a similar methodology as Marinelli et al. (2025). Groundwater use was then considered unsustainable when simulated groundwater levels fell below these thresholds due to human-induced abstractions. Sustainability, in this case, is not a binary state or a single threshold exceedance event, but rather a dynamic process. Groundwater systems may experience temporary violations of their sustainable thresholds, prolonged periods of unsustainability, or even recover from past overexploitations. Understanding these dynamics is essential for evaluating future groundwater risks and management opportunities. By identifying regions where unsustainable groundwater conditions are projected to intensify, persist, or recover, we provide a more comprehensive picture of future groundwater vulnerability than an assessment of threshold exceedance can alone.

This leads to the central research question of this study: *How will groundwater sustainability evolve across space and over time under projected climate and water use changes through 2100?* To answer this question, we evaluated monthly groundwater sustainability at 5-arcmin resolution and quantified the recurrence, persistence, seasonality, and severity of projected groundwater unsustainability. In doing so, we identified where, when, how often, and how severely groundwater levels are projected to fall below environmentally sustainable thresholds under future climate and water use conditions.

2 Methodology

2.1 Model setup

In this study we utilized a model coupling of the global-scale hydrological model VIC-WUR (Droppers et al., 2020; Liu et al., 2026) and a groundwater flow model based on MODFLOW 6 (Langevin et al., 2017). This is a one-way coupling framework, wherein VIC-WUR output (river discharge, groundwater recharge, groundwater demand) is used as input for MODFLOW. For more detailed accounts of the model framework, we refer to previous studies (Liu et al., 2026; Marinelli et al., 2025). We simulated both models globally at 5-arcmin spatial resolution (~10 x 10 km at the equator). VIC-WUR was simulated at hourly to daily timesteps with the output aggregated monthly, and MODFLOW was simulated with monthly timesteps. Our model period is 1979-2100, split into a historic period (1979-2014), current period (2015-2025), and future period (2026-2100).

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We forced VIC-WUR in the historic period with the WFDE5 bias-adjusted reanalysis climate dataset, which applied WATCH forcing data methodology to ERA5 (Cucchi et al., 2020). For the current and future periods, following the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) protocol, we forced VIC-WUR with output from the GFDL climate model under two future scenarios: a low-emission scenario (SSP1-2.6) and a high-emission scenario (SSP3-7.0) (Lange and Büchner, 2021). The climate datasets were subsequently downscaled from 30-arcmin to 5-arcmin, following previous methodology (Marinelli et al., 2025). We also forced VIC-WUR with groundwater discharge (i.e., the flux of groundwater to surface water) to improve the coupling between surface water and groundwater. To generate this forcing data, we first simulated VIC-WUR under natural conditions without the added groundwater discharge flux, directly following the approach used in a previous study (Marinelli et al., 2025). We then simulated MODFLOW under natural conditions to generate groundwater discharge values over our model period. This groundwater discharge data was then used to force VIC-WUR for all subsequent simulations, acting as a proxy for a two-way coupled modelling framework. We did this for both future scenarios to generate unique forcing files for each.

2.2 Natural simulations

With the remapped climate forcing projections from ISIMIP and the simulated groundwater discharge forcing for both future scenarios, we ran VIC-WUR from 1979-2100 (covering the full model period) under natural conditions (i.e., without any anthropogenic surface water users, land use changes, or dams). In effect, the only anthropogenic influences on these simulations come from the climate forcing data, which do account for potential trajectories of socioeconomic and emission developments (Lange and Büchner, 2021). We processed the monthly aggregated output from VIC-WUR (river discharge and groundwater recharge) as inputs to MODFLOW. Additionally, we took the 1.5-year return period of the monthly river discharge to calculate the bankfull discharge, which MODFLOW uses to estimate riverbed elevation. Then, using the simulated groundwater head from December 2014 (Marinelli et al., 2025) as the initial condition, we simulated MODFLOW from 2015-2100 under naturalized conditions (i.e., without groundwater abstractions) for both future scenarios to generate monthly values of groundwater head and groundwater discharge.

2.3 Human-impacted simulations

The human-impacted simulations introduced anthropogenic influences into the model configuration. For VIC-WUR, this amounted to surface water uses, land use changes, and dams. For MODFLOW, this amounted to groundwater uses. We included the WEL-package to simulate groundwater abstractions from a two-layer MODFLOW model with both confined and unconfined aquifers, following previous parameterizations and methodologies (de Graaf et al., 2015; de Graaf et al., 2017; de Graaf et al., 2020). For the human-impacted simulations, we used a model period of 1979-2100 (covering the full model period). We used the period 1979-2025 for spin-up, allowing the model to stabilize and buffer the change in climate forcing from December 2014 to January 2015 (the transition point between the historic and current periods). We then used the output

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from the future period, 2026-2100, for our analysis. We simulated VIC-WUR and MODFLOW with human impacts for both future scenarios.

2.3.1 Water users

We included the four main sectors of water users in our human-impacted simulations of VIC-WUR: domestic, livestock, industrial, irrigation (Döll et al., 2012; Droppers et al., 2020; Wada et al., 2014). To implement water demand and uses in the model, these sectors each require data for their total freshwater demands, groundwater fractions, and consumption fractions (Droppers et al., 2020). Freshwater demands represent the daily volume of water required by each sector. Groundwater fractions represent the share of freshwater demand that is allocated to the groundwater source, with the remaining share of water allocated to the surface water source. Consumption fractions represent the share of withdrawn surface water which is consumed, with the remaining water fed back into the system as return flows.

Freshwater demands for the domestic and industrial sectors were obtained from the ISIMIP3a (historic) and ISIMIP3b (current, future) protocols (ISIMIP, 2026b; Wada et al., 2020). The demands account for varying anthropogenic influences over the full model period, although not for climate change impacts (i.e., emission pathways) in the current and future periods (ISIMIP, 2026a). These datasets are available at 30-arcmin resolution and annual timesteps. We spatially downscaled the domestic and industrial demands to 5-arcmin using population density (CIESIN, 2017; Yan et al., 2022). We temporally downscaled the domestic and industrial demands uniformly throughout the year, so that each day within each year has the same demands. These downscaling techniques assume that domestic and industrial freshwater demands are focused where people live (Flörke et al., 2013) and do not fluctuate much within each year (Droppers et al., 2020). The livestock freshwater demands were calculated using counts of livestock for eight different species: buffaloes, cattle, chickens, ducks, horses, goats, pigs, sheep (FAO, 2026b). Additionally, the demands utilized specific water demands for each species and maximum monthly air temperature (Droppers et al., 2020). The historic livestock water demands are based on static animal counts from 2010, while the current and future livestock water demands are based on static animals counts from 2015, but the demands are dynamic in time as a function of air temperature (and are, therefore, unique per climate scenario). The irrigation demands in VIC-WUR are calculated internally for gridcells classified as irrigated. These gridcells are further distinguished between paddy and non-paddy crop types (Kebede et al., 2025). The model determines the water required to avoid crop water stress using crop-specific evapotranspiration and soil moisture and applies irrigation efficiency to estimated gross withdrawals (Droppers et al., 2020).

The groundwater fractions for the domestic and irrigation sectors are used from a previous study (Döll et al., 2012). These values are provided at 30-arcmin resolution and were conservatively remapped to 5-arcmin. For the livestock sector, the groundwater fractions are all 0, indicating that all livestock water demands are met by surface water (Droppers et al., 2020). For each of these three sectors, the groundwater fractions are static in time. For the industrial sector, we used manufacturing

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groundwater fractions (Döll et al., 2012) and simulated manufacturing and energy withdrawals (Gosling et al., 2026) to calculate total industrial groundwater fractions (as the industrial sector is comprised of the manufacturing and energy sub-sectors). Assuming that the energy sub-sector does not use groundwater, the industrial groundwater fractions were calculated using Eq. (1). For the historic period, unique industrial groundwater fractions were calculated annually given the simulated manufacturing and energy withdrawals. For the current and future periods, the industrial groundwater fractions are static based on the 2014 mean annual manufacturing and energy withdrawals.

$$GWfrac_{ind} = GWfrac_{manu} * \frac{FWwith_{manu}}{FWwith_{ind}} \quad (1)$$

where $GWfrac_{ind}$ represents the industrial groundwater fraction, $GWfrac_{manu}$ represents the manufacturing groundwater fraction, $FWwith_{manu}$ represents the manufacturing freshwater withdrawals, and $FWwith_{ind}$ represents the industrial freshwater withdrawals.

Historic consumption data accounts for varying anthropogenic influences, while current and future consumption data is based on static anthropogenic influences from 2015 (ISIMIP, 2026a). The consumption fractions for the domestic sector were calculated using the ratio of simulated water consumption to simulated water withdrawals. For the industrial sector, the historic consumption fractions were calculated using this same approach (ratio of consumption to withdrawals). For the current and future period, industrial consumption was calculated using specific energy consumption fractions per gridcell in locations with thermoelectric powerplants (Droppers et al., 2020) and a standard manufacturing consumption fraction of 0.1 (Shiklomanov, 2000). These consumption fractions were then scaled based on the ratio of energy and manufacturing withdrawals to total industrial withdrawals, as shown in Eq. (2). The consumption fraction for the livestock sector was set to 1, indicating that all water withdrawn for livestock is consumed (Droppers et al., 2020). Irrigation consumption fractions are calculated internally by VIC-WUR based on the simulated evapotranspiration (Droppers et al., 2020).

$$cons_{ind} = \frac{cons_{energy} * with_{energy} + 0.1 * with_{manu}}{with_{energy} + with_{manu}} \quad (2)$$

where $cons_{ind}$ represents the industrial consumption fraction, $cons_{energy}$ represents the energy consumption fraction, $with_{energy}$ represents the energy freshwater withdrawals, and $with_{manu}$ represents the manufacturing freshwater withdrawals.

In addition to local water withdrawals at the gridcell level, VIC-WUR represents remote withdrawals as short-range surface water transfers from predefined donor cells to water-deficient recipient cells. The donor-recipient pairs are constructed from the river routing network by identifying potential donor cells for upstream recipient cells in the vicinity, while excluding those on the direct river path. During the simulation, remote withdrawals are only activated when a recipient cell has unmet water demand after local withdrawals from surface water resources. For each donor cell, the model aggregates the total unmet

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demand from all of its connected recipient cells, determines the available water to be distributed, and allocates this volume proportionally across the recipient cells. The remotely withdrawn water is then removed from the donor cell's routed discharge.

2.3.2 Land use changes

For the land use forcing to VIC-WUR, we expanded on previous applications of the model (Droppers et al., 2020) to include four crop coverage classes: irrigated paddy, rainfed paddy, irrigated non-paddy, rainfed non-paddy. We aggregated data from 23 crop classes into paddy (rice) and non-paddy (all other crop classes), and the coverage for each class was already specified as irrigated or rainfed (Kebede et al., 2025). Data for these classes was available at monthly timesteps for four reference years in our model period (2000, 2005, 2010, 2015). For the period 1979-1999 we backcast the crop coverage fractions from 2000; for the intervening years between the reference years, we linearly interpolated changes in crop coverage fractions using the values for each specific month (i.e., January values from 2000 and 2005 were used to linearly interpolate the January values for 2001-2004); and for the period 2016-2100 we forecast the values from 2015. In effect, this meant our crop coverage was fully dynamic from 2000-2015 and only varied monthly (not annually) from 1979-1999 and 2016-2100. We then added these dynamic crop coverage fractions to the static coverage fractions from the other land use classes present in previous VIC-WUR simulations (Droppers et al., 2020). With these new totals, we filled in the remaining land as barren soil (in the cases that the aggregated coverage fractions were less than 1). In cases where the aggregated coverage fractions were greater than 1, we uniformly scaled all the land use classes down to ensure the total coverage fractions would equal 1. Therefore, for each gridcell, there were 11 static land use classes and 5 dynamic land use classes (four crop types and barren soil).

2.3.3 Dams

The last addition to the human-impacted VIC-WUR configuration was the inclusion of dam operations (Lehner et al., 2024). We represented 7,983 dams globally, selected using a data quality threshold of level 4 or better (as defined in the dataset) and a minimum reservoir capacity of 20 million m^3. For each dam, the model registers its location, storage capacity, and servicing area. During the simulation, if local water availability in a servicing cell is insufficient to meet the demand, water can be released from the reservoir to augment the surface water supply. Dam storage is updated dynamically based on the upstream inflow and dam release conditions. With all these human-impacted configurations implemented, we simulated VIC-WUR from 1979-2100 under both climate scenarios.

2.3.4 Groundwater abstractions

To simulate MODFLOW with human-impacts, we introduced the WEL package to the model configuration (Langevin et al., 2017). This package allows for groundwater abstractions from the bottom layer of the two-layered MODFLOW model (where the top layer can act as a confining layer) and the center of each gridcell (de Graaf et al., 2017). Simulating groundwater abstractions from both confined and unconfined aquifers allows for realistic changes in groundwater storage (de Graaf et al.,

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2017). The groundwater abstractions are based on the groundwater demands, but limited by the pumping capacity of each aquifer. As MODFLOW is not set up to differentiate between sectoral water users, we aggregated the groundwater demands across all sectors. For the domestic and industrial sector, the groundwater demands were calculated by multiplying the groundwater fractions by the freshwater demands. For the irrigation sector, we used the VIC-WUR output of irrigation surface water demand and the irrigation groundwater fractions to calculate the irrigation groundwater demand, as seen in Eq. (3). Livestock groundwater demands were not calculated, as livestock freshwater demands are fully met by surface water in our model framework. Finally, we included unmet surface water demands from VIC-WUR in the groundwater demands, assuming that shortages of surface water availability will be supplemented by groundwater (Sutanudjaja et al., 2018).

$$GWdem_{irr} = \frac{GWfrac_{irr}}{1-GWfrac_{irr}} * SWdem_{irr} \quad (3)$$

where $GWdem_{irr}$ represents the irrigation groundwater demand, $GWfrac_{irr}$ represents the irrigation groundwater fraction, and $SWdem_{irr}$ represents the irrigation surface water demand.

The pumping capacity dataset (Sutanudjaja et al., 2018) provides maximum limits of groundwater abstractions for global aquifers in billion cubic meters per year from 1979-2015. We then applied the 2015 pumping capacities from 2016-2100. To apply this data to our monthly gridded groundwater demands, we generated scaling factors for each gridcell and month. For each year, we aggregated the total monthly groundwater demands of all gridcells within each aquifer. We then calculated the share of total annual groundwater demand within each aquifer that came from each monthly gridcell. Finally, these factors were applied to the pumping capacity data to dynamically downscale the annual pumping capacities into monthly, gridded pumping capacities. In effect, this means that if an aquifer has groundwater demands exceeding its pumping capacity, the groundwater demands in each location and for each timestep will be uniformly scaled down. If the groundwater demands do not exceed the pumping capacity, all the groundwater demands can be satisfied. Lastly, while the total pumping capacities per aquifer from 2015-2100 were static, the spatiotemporal downscaling did vary as a function of the distribution of groundwater demands. Finally, after generating the groundwater abstractions dataset, we simulated MODFLOW with monthly timesteps under these human-impacted conditions to calculate groundwater head and groundwater discharge for each gridcell for both climate scenarios.

2.4 Model validation

We validated our human-impacted model results using both VIC-WUR and MODFLOW output from the SSP3-7.0 climate scenario. Our validation period spans 1994-2022. The model evaluation was based on three key variables: groundwater head compared to observations (Bäthge et al., 2026), source withdrawals (water use from groundwater, surface water, and total freshwater) compared to reported national statistics from AQUASTAT (FAO, 2026a), and river discharge compared to observations (GRDC, 2026). For the groundwater head, we took the mean values per year for comparison with the observed

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dataset (also annually averaged where necessary for compatibility). For the source withdrawals, we aggregated our gridded results within each year to the national scale and compared these with the reported data where it was available. For the river discharge, we compared the simulated output with observations for 663 global gauging stations to assess the influence of including the groundwater discharge forcing in VIC-WUR (Liu et al., 2026). We statistically evaluated the model output against the observed and reported values using correlation (Spearman, 1904), efficiency (Nash and Sutcliffe, 1970), and percent bias.

2.5 Estimating sustainable groundwater head

Using the MODFLOW output from the natural simulations, we estimated sustainable groundwater head thresholds globally and at monthly timesteps from 2026-2100. We defined sustainable groundwater head using low-flow metrics of groundwater head and groundwater discharge, assuming the 10th percentile (90th percent exceedance) represents the low-flow state (Marinelli et al., 2024; Marinelli et al., 2025). To summarize this methodology, our approach calculates the 10th percentile of natural groundwater head, h_{90}, from a moving 60-month window as an initial estimation of the sustainable groundwater head threshold, as seen in Eq. (4). In most instances, these values can be used as the sustainable threshold, but not during low-flow periods, moments of river infiltration (when surface water flows to groundwater), or in disconnected groundwater-surface water systems. To account for these three situations, we also calculated the 10th percentile of natural groundwater discharge, Q_{90}, using this same approach, as seen in Eq. (5) (Marinelli et al., 2024). We then updated our estimates of sustainable groundwater head thresholds to stipulate that they are equal to the natural groundwater head for a given timestep if the Q_{90} is less than or equal to 0, the natural groundwater discharge is less than or equal to 0, or if the natural groundwater discharge is less than the Q_{90}, as seen in Eq. (6). Essentially, these caveats ensure that the natural system (i.e., without anthropogenic influences) can never cause the groundwater head to drop below the sustainable threshold, or that more river infiltration would need to be induced to attain sustainability.

$$h_{90} = \frac{Ph_{90} - N_{60}}{100} \quad (4)$$

where h_{90} represents the low-flow threshold for groundwater head, P_{90} represents the 10th percentile of natural groundwater head, and N_{60} represents the 60-month moving window used to calculate the running percentile.

$$Q_{90} = \frac{PQ_{90} - N_{60}}{100} \quad (5)$$

where Q_{90} represents the low-flow threshold for groundwater discharge, P_{90} represents the 10th percentile of natural groundwater discharge, and N_{60} represents the 60-month moving window used to calculate the running percentile (Marinelli et al., 2024).

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$$h_{sus} = \begin{cases} h_{90} \; if \; Q_{90} > 0 \wedge Q > 0 \wedge Q \geq Q_{90} \\ h \; if \; Q_{90} \leq 0 \vee Q \leq 0 \vee Q < Q_{90} \end{cases} \quad (6)$$

where h_{sus} represents the sustainable groundwater head threshold, h_{90} represents the low-flow threshold for groundwater head from Eq. (4), Q_{90} represents the low-flow threshold for groundwater discharge from Eq. (5), Q represents the natural groundwater discharge, and h represents the natural groundwater.

2.6 Experimental setup

We processed the output from our natural and human-impacted simulations to focus on relevant locations for groundwater sustainability assessments. This step excluded cells with poor temporal coverage over the full model period (i.e., groundwater discharge in less than 10% of all timesteps), limited groundwater-surface water interactions for any given timestep (i.e., groundwater discharge equal to 0), and cells outside of relevant aquifers that are able to be captured by the 5-arcmin resolution of our model (de Graaf et al., 2015; Marinelli et al., 2024; Marinelli et al., 2025). We then assessed projected groundwater sustainability by comparing the groundwater head from the human-impacted run to the sustainable groundwater head thresholds from the natural run. A gridcell was classified as unsustainable whenever the human-impacted head fell below the sustainable threshold. These comparisons were performed monthly for 2026-2100 under both future scenarios. We determined when crossing of these sustainable boundaries is projected to occur, as well as the degree to which groundwater use is projected to be unsustainable. With this information, we then assessed the frequency, severity, timing, and duration of unsustainable groundwater use through the end of the century.

2.6.1 Assessing occurrences of groundwater unsustainability

For each gridcell and timestep, we calculated if the human-impacted groundwater head is projected to be at unsustainable levels. This gives a binary indication of sustainability or unsustainability. We were then able to calculate the unsustainable frequency within each gridcell, defined here as the proportion of months during which groundwater head falls below the sustainable threshold. We calculated the unsustainable frequency at multiple time intervals and for both SSP1-2.6 and SSP3-7.0, enabling comparisons temporally and between future scenarios.

We first assessed groundwater unsustainability during the full future period (2026-2100) for all gridcells. Taking the mean of unsustainable conditions over all timesteps gave us a broad indication of the overall occurrence and spatial patterns of projected groundwater unsustainability. This output showed us where unsustainable groundwater conditions are projected to occur most often and allowed us to identify hotspots of groundwater overexploitation in regions with consistently high values. Furthermore, using the binary occurrences of groundwater unsustainability, we calculated the maximum duration of groundwater unsustainability per gridcell, defined here as the longest consecutive period of unsustainable groundwater conditions. This metric provides a single value per gridcell and can be used to distinguish between intermittent and continuous unsustainable conditions.

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We then assessed the progression of groundwater unsustainability over 25-year intervals (2026-2050, 2051-2075, 2076-2100). We used the long-term mean values of unsustainable frequency as the baseline (per future scenario) and compared the 25-year unsustainable frequency values to these baselines. This comparison shows the increases or decreases in the occurrences of unsustainable groundwater conditions for each time interval, relative to the long-term mean, highlighting how groundwater unsustainability is projected to evolve through the end of the century. Furthermore, we conducted these analyses at the aquifer-scale by taking the mean values within each aquifer extent. This analysis served to evaluate the extent of larger-scale unsustainable conditions across extended time periods and highlight where short-term issues require immediate actions and where long-term issues can build up without interventive measures.

Similarly, we assessed the seasonality of unsustainable groundwater conditions using unsustainable frequency values averaged over each calendar month (for the full future period). Once again using the long-term mean values as the baseline (per future scenario), we assessed whether unsustainable conditions are projected to be more or less frequent, relative to the baseline, for each month of the year. These values were also upscaled to the aquifer-scale by taking the mean values within each boundary. This analysis served to ascertain which periods of the year are most at-risk for groundwater unsustainability and require changes in management practices to prevent unsustainable conditions from occurring.

Lastly, we carried out an annual analysis of the progression of unsustainable groundwater frequency in four selected hotspots regions of groundwater overexploitation: Indo-Gangetic Plain, North China Plain, Central Valley, High Plains. Here, we used the mean annual unsustainable frequency within each hotspot region (using multiple aquifers which make up each region) for each year from 2026-2100. We then compared these annual progressions between future scenarios to evaluate how occurrences of groundwater unsustainability are projected to evolve through the end of the century in known areas of groundwater stress. This analysis showed us both how projected unsustainable groundwater frequency changes annually, as well as how the projections differ between scenarios. In regions where groundwater management practices need to be highly scrutinized to ensure sustainability, it is crucial to identify pathways for unsustainable conditions to progress over time. Ultimately, by evaluating the frequency of groundwater unsustainability over varying time periods, we were able to identify long-term, short-term, and seasonal trends to characterize the spatial and temporal patterns in projected groundwater sustainability.

2.6.2 Assessing the severity of groundwater unsustainability

In addition to calculating whether groundwater unsustainability is projected to occur, we also calculated the severity of unsustainable conditions when they do occur. Here, we define unsustainable severity as the degree to which human-impacted groundwater head drops below the sustainable threshold, with negative values representing unsustainable groundwater levels.

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While more negative values indicate a higher degree of unsustainable severity, it should be noted that any drops below the sustainable thresholds would have harmful environmental and ecological impacts.

As with the unsustainable frequency, we first assessed unsustainable severity using mean values per gridcell over the full future period (2026-2100) for both future scenarios. Unsustainable severity values are only taken for gridcells with unsustainable conditions in a given timestep. This analysis over all years in the future period highlights locations which are projected to experience the highest degree of unsustainable groundwater conditions relative to their sustainable thresholds and can be used to identify where adaptive and mitigative measures are most necessary to ensure sustainability.

We also assessed the annual progression of unsustainable severity in the same four hotspot regions identified in Section 2.6.1 for both future scenarios. Using the median values per region, we calculated how unsustainable groundwater severity will change annually and differ between climate and socioeconomic pathways. This once again serves to evaluate the evolution of groundwater unsustainability over time in four highly stressed regions, as well as to identify the influence of each future scenario on unsustainable conditions. By conducting our analyses of unsustainable severity at various spatial and temporal scales, we assessed the environmental impacts associated with different degrees of groundwater unsustainability.

3 Results

3.1 How often will groundwater use be unsustainable?

Our findings project widespread groundwater unsustainability through the end of the century. Across both future scenarios, 89% of gridcells with relevant groundwater-surface water interactions experience at least one period of groundwater unsustainability. While this result indicates a vast spatial distribution of unsustainable groundwater use, occurrences are more often projected to be intermittent than continuous, with mean and median frequencies of 37% and 29% (Fig. 1 and A1). This is further supported by the longest duration of unsustainable periods, with global means of 159 months (~13 years) and medians of 42 months (3.5 years). The large difference between mean and median values indicates a skewed distribution, with many regions experiencing episodic unsustainability and a smaller number of hotspots experiencing persistent periods of unsustainability. Such hotspots are located in the Indian subcontinent, eastern Asia, central and western North America, tropical Africa and South America, and several high-latitude regions across North America, Europe, and Asia. The differences between scenarios are negligible at the global scale, with both mean and median deviations of 0.1%. At the gridcell scale, the differences are also small, with the majority of gridcells deviating by less than 2.6% in frequency, and 86% of gridcells deviating by less than 10% (Fig. A2). SSP3-7.0 produces modest increases in unsustainable frequency in the tropics, while SSP1-2.6 produces increases in permafrost regions. While our results indicate a vast spatial distribution of unsustainable groundwater use, occurrences are more often projected to be intermittent than continuous.

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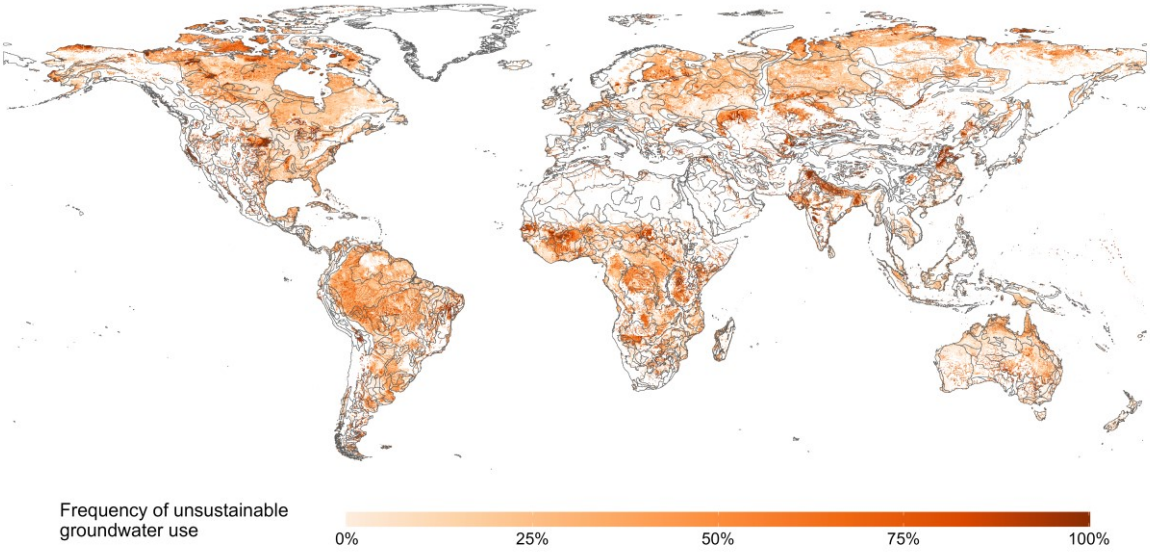

Figure 1: Mean unsustainable frequency of groundwater use from 2026-2100 under the SSP3-7.0 future scenario. A value of 0% indicates groundwater use is never projected to be unsustainable, a value of 50% indicates groundwater use is projected to be unsustainable in half of all timesteps, a value of 100% indicates groundwater use is always projected to be unsustainable.

The assessment of groundwater sustainability at the aquifer scale reveals substantial temporal shifts in the occurrence of unsustainable groundwater use through the end of the century. Separated into early-century (2026-2050), mid-century (2051-2075), and late-century (2076-2100) intervals, our results show a non-linear progression of unsustainable groundwater use across both future scenarios (Fig.2 and A3). Relative to the full-period means (unique to each scenario), the early-century period shows moderate deviations in unsustainable frequency, with 29% of aquifers exhibiting above-average unsustainable conditions. The mid-century period shows a relative decrease in unsustainability, with 25% of aquifers exceeding their long-term mean, suggesting a temporary easing of pressure on groundwater resources. In contrast, the late-century period shows a marked intensification of groundwater unsustainability, characterized by 38% of aquifers exceeding their long-term mean frequency of unsustainable conditions. When weighted by aquifer area, this late-century increase is even more pronounced, accounting for 40% (SSP3-7.0) and 52% (SSP1-2.6) of total global aquifer extent.

This tendency towards greater late-century groundwater unsustainability is further reflected in the distribution of peak unsustainable conditions. Across scenarios, 40% of aquifers reach their maximum unsustainable frequency during the late-century, compared with 28-32% during the earlier periods. The area-weighted results again show a pronounced late-century dominance of unsustainability, with 40% (SSP3-7.0) and 52% (SSP1-2.6) of aquifer extent experiencing peak frequencies in this period (compared with 20-34% in the earlier periods). These patterns vary little between scenarios, with the majority of

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aquifers differing by less than 2% in unsustainable frequency across all time periods, and 91% (early-century), 89% (mid-century), and 86% (late-century) of aquifers differing by less than 10% between scenarios (Fig. A4).

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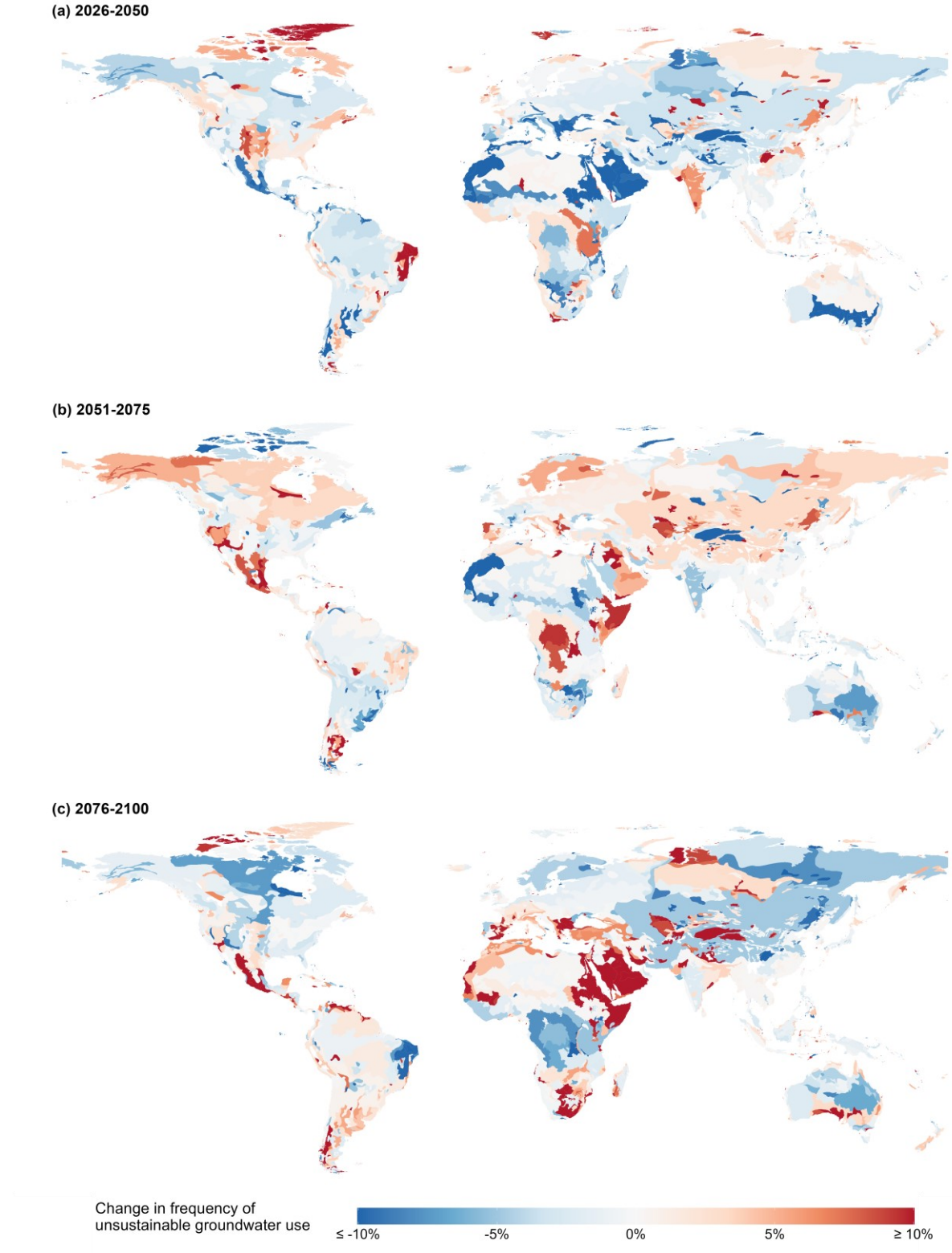

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Figure 2: Difference in unsustainable frequency of groundwater use over 25-year intervals from 2026-2100, when compared to the mean over the full future period, for the SSP3-7.0 scenario. Results are aggregated over aquifer extents. Red aquifers indicate the unsustainable frequency in that specific time period will be more frequent than the mean over the full period, while blue aquifers indicate the unsustainable frequency in that specific time period will be less frequent than the mean over the full period.

To further examine seasonal variability in projected groundwater sustainability, we evaluated monthly deviations in unsustainable groundwater frequency relative to the full-period mean for each aquifer and scenario (Fig. A5 and A6). Unlike the 25-year progression analysis, which captures long-term temporal evolution, this analysis isolates seasonal variability by highlighting months in which unsustainable conditions are systematically above or below the long-term mean. Positive and negative deviations, therefore, reflect seasonal amplification and attenuation of groundwater overexploitation. Seasonal variability in unsustainable groundwater conditions is widespread across aquifers and exhibits limited sensitivity to future scenarios. Mean seasonal amplitudes indicate a 17% intra-annual variation in unsustainable frequency globally, while median values indicate a 12% variation. In 10% of aquifers with particularly strong seasonal behavior, amplitudes exceed 40% (SSP3-7.0) and 44% (SSP1-2.6). Overall, 71% of aquifers experience moderate seasonality (amplitudes exceeding 5%) and 56% experience strong seasonality (amplitudes exceeding 10%), demonstrating that seasonal fluctuations in groundwater unsustainability are a common feature across global aquifer systems. Spatially, seasonality presents regionally rather than locally. High-latitude regions across North America, Europe, and Asia, as well as regions in central and east Asia, are generally projected to experience above-average unsustainability from February-June; tropical South America and southern Africa from November-March; south Asia from April-August. The distribution of peak unsustainability months also suggests slightly more pronounced seasonality under SSP1-2.6.

To focus our analysis on regional-scale patterns, we examined mean frequencies of unsustainable groundwater use in four hotspots: High Plains, North China Plain, Central Valley, Indo-Gangetic Plain (Fig. 3). All four regions exhibit high levels of groundwater unsustainability through the end of the century and remain highly vulnerable under both future scenarios. While the magnitude and sensitivity vary between regions, there are minimal differences in which scenario produces more frequent unsustainable conditions, with values often fluctuating throughout the future period.

Of these regions, the High Plains shows the greatest inter-annual variability, with large oscillations in scenario differences causing median unsustainable frequencies within the region to vary between 51-93%. This sensitivity to future scenario reaches a peak between 2039-2045, when unsustainability under SSP3-7.0 conditions is projected to be up to 40% more frequent than under SSP1-2.6 conditions. In the North China Plain, there are slightly more prolonged periods where one future scenario produces more frequent unsustainability than the other (e.g., SSP3-7.0 from 2047-2055, SSP1-2.6 from 2066-2082). This response indicates that the system is not as susceptible to short-term fluctuations, but rather long-term trends in climate and hydrogeological conditions. The Central Valley is projected to maintain the highest overall levels of unsustainable groundwater

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frequency at 91% (averaged over the future period), with a slight upward trend indicating that groundwater unsustainability will worsen towards the end of the century. In contrast, the Indo-Gangetic Plain is projected to experience the lowest rate of groundwater unsustainability of these four regions, with median values throughout the century of 62%. Additionally, this region is projected to have the smallest divergence between scenarios, with both producing similar unsustainable trajectories.

Overall, while these regional responses do not indicate a uniform response in groundwater unsustainability, all four hotspot regions remain highly vulnerable under both future scenarios, highlighting the persistence of groundwater stress regardless of future scenario.

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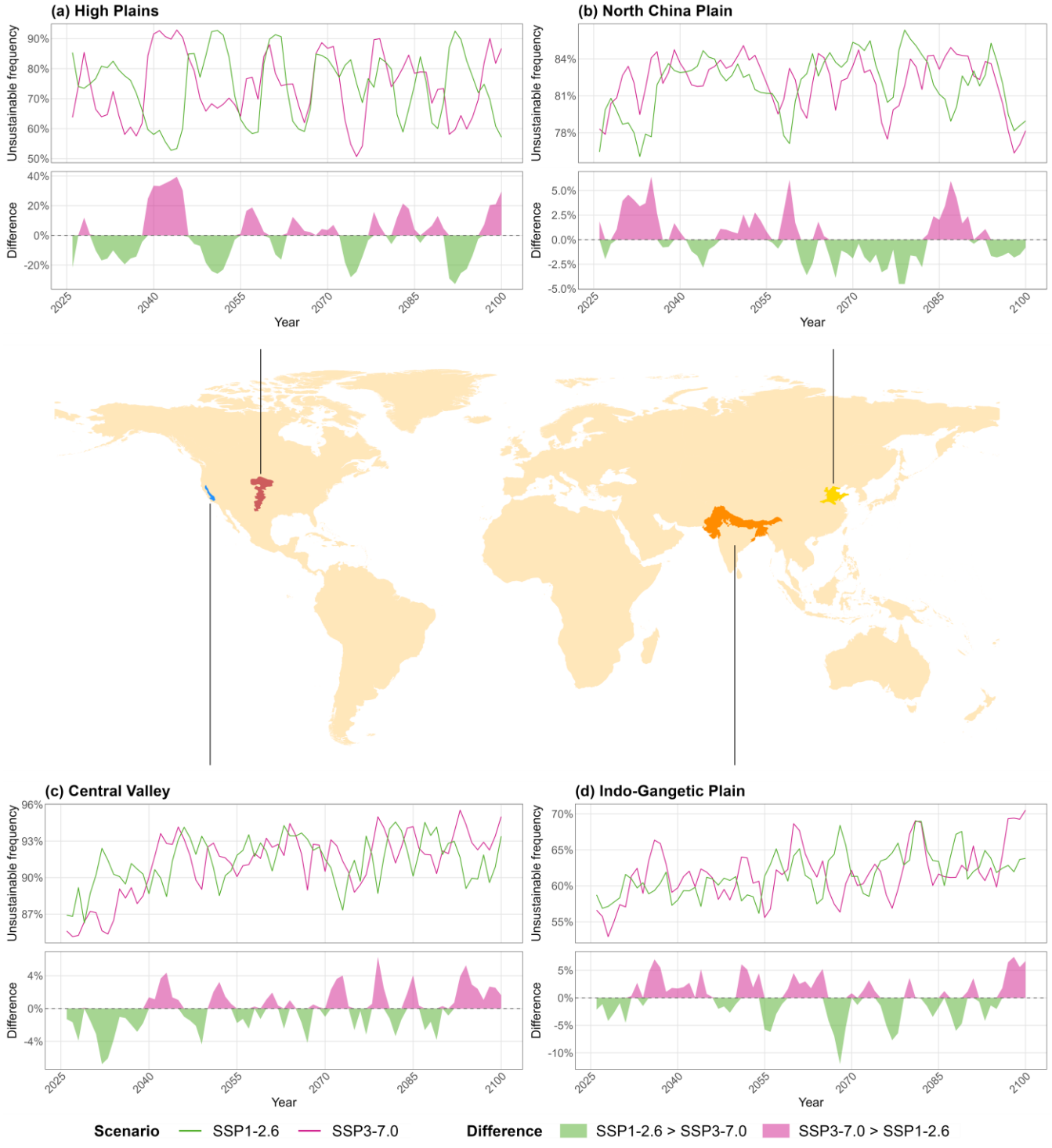

Figure 3: Progression of unsustainable groundwater frequency from 2026-2100 under both future scenarios, including the difference between the two, aggregated over four hotspot regions.

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3.2 To what degree will groundwater resources be overexploited?

The severity of projected groundwater unsustainability is substantially more concentrated than the frequency. Across both future scenarios, global median severity remains small, with groundwater levels falling only 0.0066 m below the sustainable threshold, while mean severities reach 0.25 m (Fig. 4 and A7). The large disparity between mean and median values indicates a highly skewed distribution of global severity, with most locations experiencing relatively modest groundwater unsustainability and a limited number of hotspots experiencing more extreme crossings of their sustainable boundaries. This pattern is reflected by the spatial distribution of severity, where, averaged over the future period, fewer than 8% of gridcells fall more than 0.1 m below their sustainable thresholds, and fewer than 2% of gridcells fall more than 1 m below their thresholds. Furthermore, 96% of total groundwater unsustainability is concentrated within just 10% of gridcells, demonstrating that the largest severities are highly localized. Although the severity of groundwater unsustainability is generally small, its potential implications depend on the system's sensitivity to threshold exceedances, as even small drops below sustainable levels cause imbalances which can have significant impacts for ecological systems. Major hotspots are present in the Indo-Gangetic Plain, North China Plain, Central Valley, and High Plains, indicating that while groundwater unsustainability may be widespread globally, the largest degrees of unsustainability are concentrated within a few highly impacted regions. The differences in unsustainable groundwater severity between the future scenarios are also small (Fig. A8). Spatially, the distribution of hotspots remains unchanged between scenarios, but with SSP3-7.0 producing more severe groundwater unsustainability. Fewer than 1% of gridcells differ by more than 1 m between scenarios, and 99% of gridcells differ by less than 0.5 m.

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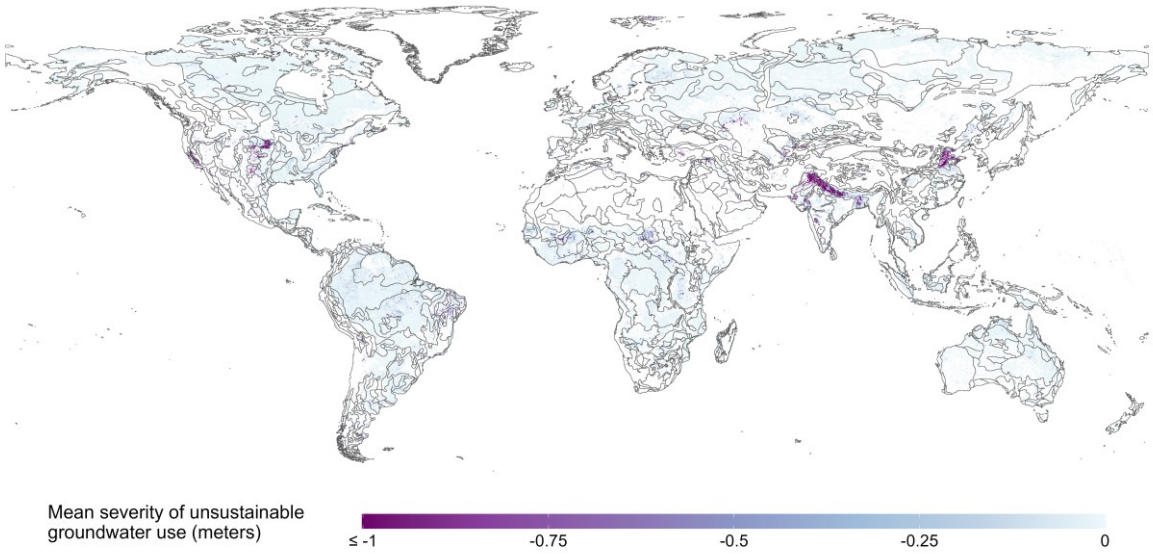

Figure 4: Mean unsustainable severity of groundwater use from 2026-2100 under the SSP3-7.0 future scenario. Negative values indicate how far below the sustainable threshold the groundwater head is projected to be.

To evaluate regional-scale changes in unsustainable groundwater severity, we examined median annual severity within the same four hotspot regions identified in Section 3.1: High Plains, North China Plain, Central Valley, Indo-Gangetic Plain (Fig. 5). The influence of future scenarios on groundwater unsustainability severity varies substantially between regions. The High Plains and Indo-Gangetic Plain display the smallest divergence between scenarios, with mean unsustainable severities differing by less than 0.01 m over the future period. Similarly, there are near even rates of more severe unsustainability occurring under both future scenarios in these two regions without clear long-term trends. They also show the smallest median unsustainable severities, with groundwater levels never dropping more than 0.33 m below their projected sustainable thresholds. In contrast, the North China Plain and Central Valley show stronger divergences between future scenarios. In the North China Plain, SSP1-2.6 severity is 0.16 m more unsustainable on average (and in 72% of years), with a particularly large difference in the mid-century (0.25 m). Ultimately, this trend is reversed towards the end of the century, with more severe SSP3-7.0 unsustainability from 2091-2100 (at a rate of 0.28 m). The Central Valley, on the other hand, is projected to consistently experience more severe unsustainable conditions under SSP3-7.0 (88% of years), with a mean difference of 0.16 m. The signal in the Central Valley also gets stronger over time, with SSP3-7.0 unsustainable frequency increasing in each progressive period through the end of the century. The largest differences are projected to occur between 2074-2091, when SSP3-7.0 unsustainability is, on average, 0.35 m more severe. These contrasting responses indicate that future socioeconomic and emissions pathways can substantially influence the severity of groundwater unsustainability in some regions, particularly the North China Plain and Central Valley, while having lesser influences in other regions, such as the High Plains and Indo-Gangetic Plain.

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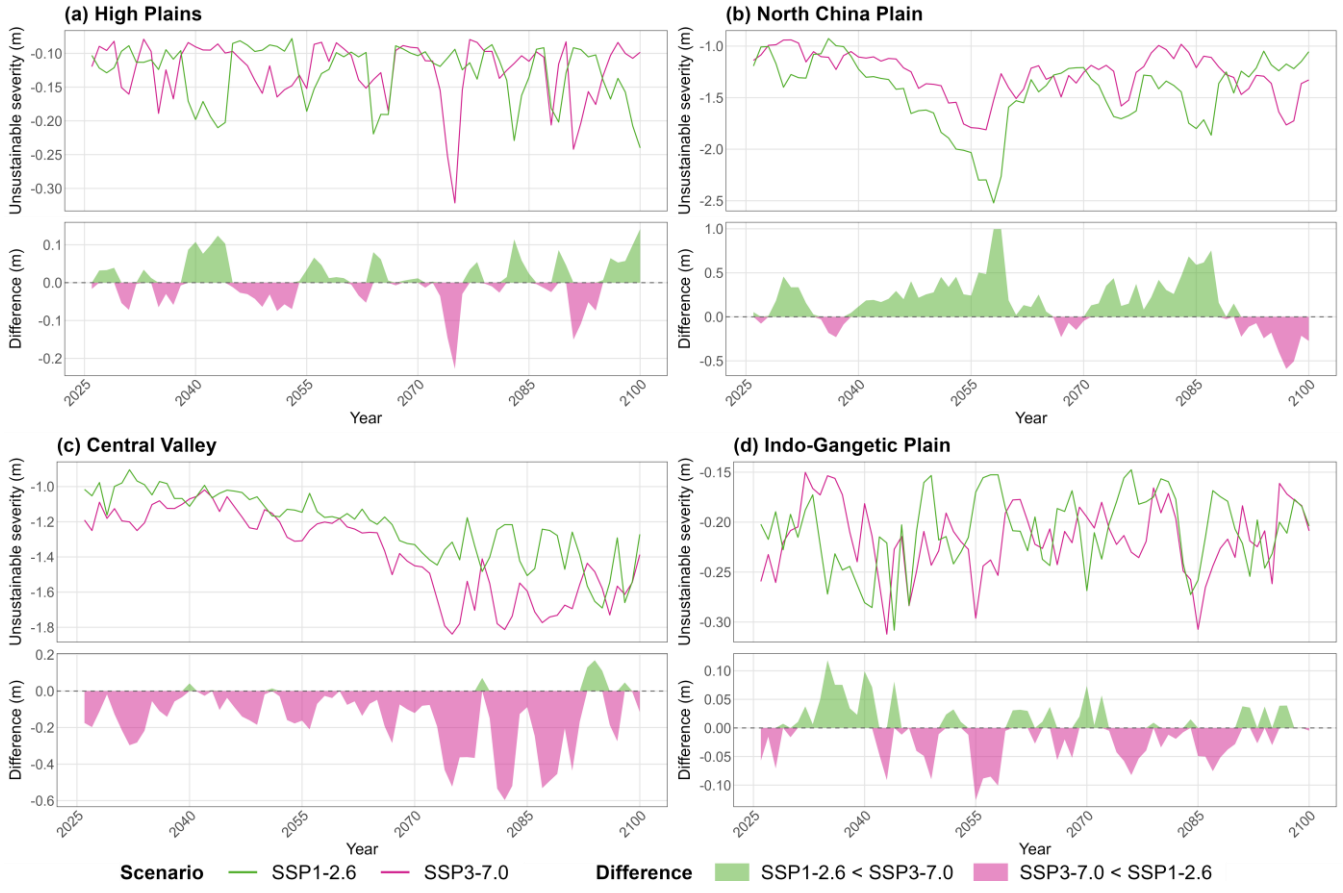

Figure 5: Progression of unsustainable groundwater severity from 2026-2100 under both future scenarios, including the difference between the two, aggregated over four hotspot regions. Negative values indicate how far below the sustainable threshold the groundwater head is projected to be.

3.3 Validation of simulated output

The validation results demonstrate strong agreement between the coupled VIC-WUR-MODFLOW framework and observed data across all evaluated variables. The validation of mean national groundwater heads over the validation period (1994-2022) shows excellent agreement between the simulated MODFLOW output and observations (r = 1, NSE = 0.99, PBIAS = -6.4%; Fig. 6a). Similarly, simulated groundwater withdrawals show strong agreement with reported values (r = 0.98, NSE = 0.94, PBIAS = 5%; Fig. 6b). The river discharge validation against observations shows that including the groundwater discharge forcing in VIC-WUR improved the simulation of river low-flows (Fig. A9), when streamflow is largely supported by groundwater. Globally, the mean correlation across all gauging stations increased from 0.60 to 0.65, while the percent bias improved from -56% to 7%. The validation of simulated surface water withdrawals from VIC-WUR and freshwater

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withdrawals (aggregate of groundwater and surface water withdrawals) against reported values also shows strong agreement, with correlations of 0.96 and 0.97 and efficiencies of 0.81 and 0.89, respectively.

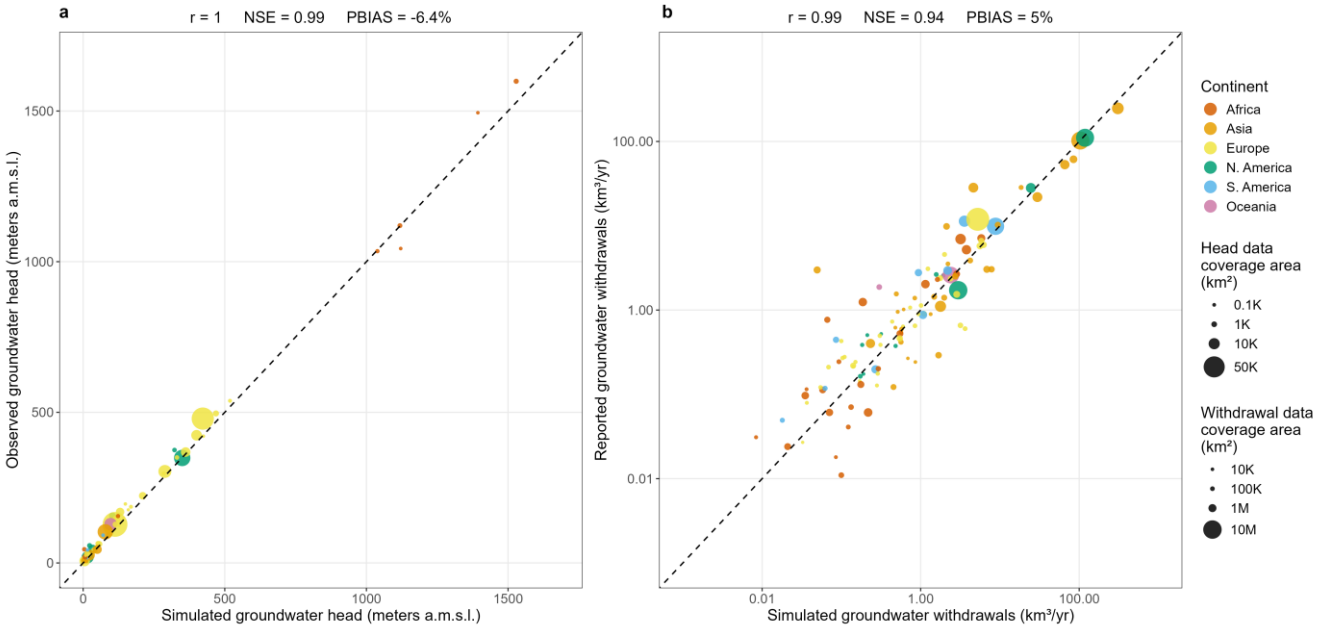

Figure 6: Groundwater head (a) and groundwater withdrawal (b) validation for the coupled VIC-WUR-MODFLOW framework. Data is presented nationally (grouped by continent) and averaged over the validation period, 1994-2022. The groundwater head coverage area represents the area of gridcells with groundwater head observations per nation, the groundwater withdrawals coverage area represents the area per nation. The simulated results are from the SSP3-7.0 human-impacted run.

4 Discussion

4.1 Evolution of projected groundwater sustainability

Our results demonstrate that projected groundwater unsustainability is widespread, with 89% of gridcells experiencing at least one period of unsustainable groundwater use due to groundwater pumping. This suggests that the exceedance of environmentally sustainable groundwater thresholds may become a common feature of many groundwater systems throughout the 21st century. The frequency, duration, and severity of these exceedances, however, vary greatly across regions. Projections of the most severe unsustainable groundwater use are concentrated in a limited number of hotspot regions, including the Indo-Gangetic Plain, North China Plain, Central Valley, and High Plains (Famiglietti, 2014; Scanlon et al., 2023; Wada et al., 2012). These contrasting spatial patterns of unsustainable frequency and severity of groundwater use indicate that groundwater sustainability should be evaluated as a dynamic process rather than through threshold are exceedance alone. While many regions may experience recurring crossings of sustainable boundaries, the associated hydrological and ecological consequences are likely to depend on the severity and duration of those exceedances.

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An important finding is the differing sensitivity of unsustainable frequency and severity to future scenarios. Across most regions, the occurrence of unsustainable groundwater use remains similar between SSP1-2.6 and SSP3-7.0. This suggests that many groundwater systems are already operating close to their environmentally sustainable thresholds, resulting in comparable rates of threshold exceedance under both scenarios. In contrast, the severity of unsustainable groundwater conditions shows greater sensitivity to future scenario pathways, particular in heavily stressed regions such as the North China Plain and Central Valley. These contrasting responses indicate that future climate and water projections have a stronger influence on the magnitude of groundwater unsustainability than on the occurrence of threshold exceedance itself. Consequently, mitigation and adaptation measures may be more effective at limiting the severity of unsustainable groundwater use rather than fully preventing threshold exceedance in highly stressed regions.

The projected increase in groundwater unsustainability towards the end of the century further emphasizes the long-term consequences of current groundwater management practices. Although the progression of unsustainable frequency is non-linear, the late-century period contains both the largest share of aquifers experiencing above-average unsustainability and the largest share reaching peak unsustainable conditions. Given the long response times of many groundwater systems, these findings suggest that groundwater management decisions implemented in the nearer term may influence sustainability through the end of the century. Similar conclusions have been drawn by previous groundwater sustainability assessments (de Graaf et al., 2019; Gleeson and Richter, 2018), demonstrating that delayed groundwater responses can cause environmental flow thresholds to be exceeded long after abstractions occur. The increased prevalence of late-century unsustainability, therefore, highlights the importance of preventive intervention strategies aimed at reducing groundwater abstractions in at-risk regions, improving irrigation efficiency, and promoting integrated management of groundwater and surface water resources.

Beyond the decadal assessment, the pronounced seasonal patterns of groundwater unsustainability observed in many aquifers further demonstrate the value of conducting assessments at monthly timescales. In several regions, projected unsustainable groundwater use occurs preferentially during specific seasons, highlighting the importance of distinguishing between the timing and frequency of threshold exceedance. Many aquifers in South Asia, for example, are projected to experience higher rates of groundwater unsustainability between April and August. One possible explanation is that sustainable groundwater head thresholds increase during the monsoon season when natural groundwater recharge and groundwater discharge rates also increase, while the human-impacted groundwater head fails to recover sufficiently to meet these changing environmental requirements. Similar seasonal mechanisms may contribute to the patterns observed in tropical South America, southern Africa, and central Asia, which also experience higher rates of groundwater unsustainability coinciding with wetter periods.

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Although the projected severity of groundwater unsustainability is generally small, the ecological significance of these exceedances should not be underestimated. The sustainable groundwater thresholds used in this study are derived from environmental flow considerations and represent groundwater levels required to maintain environmentally critical low-flow conditions in connected surface water systems . As a result, even modest declines below these thresholds indicate that groundwater abstractions reduce the capacity of groundwater systems to support environmentally critical low-flow conditions. The sensitivity of ecosystems to such exceedances likely varies spatially depending on local hydrogeological and ecological characteristics, but the widespread occurrence of groundwater unsustainability indicates an increased risk of negative environmental impacts, even where groundwater head declines appear limited.

Finally, our results highlight the potential role of large-scale climate variability in shaping future groundwater sustainability. While this study focuses on long-term climate and water-use pathways rather than specific projections of climate variability, phenomena such as the El Niño-Southern Oscillation may influence the timing and severity of unsustainable groundwater conditions by altering precipitation, recharge, and irrigation demand. Periods of anomalously wet conditions may temporarily reduce groundwater stress through increased recharge, whereas prolonged droughts associated with climate variability could amplify groundwater depletion and increase the duration and severity of unsustainable conditions. Although these mechanisms were not explicitly evaluated in this study, future work could examine the extent to which inter-annual climate variability and extreme conditions contribute to temporal fluctuations in groundwater sustainability.

4.2 Comparison with previous assessments

The projected patterns of groundwater unsustainability identified in this study are broadly consistent with previous global assessments, while providing additional insight into the temporal dynamics of future groundwater sustainability. Previous work demonstrated that environmental flow limits have been or are projected to be exceeded across many of the world's major aquifer systems during the 20th and 21st centuries (de Graaf et al., 2019). Similarly, historic assessments have shown that groundwater unsustainability has already emerged across large portions of the globe, with particularly severe impacts concentrated in highly-irrigated agricultural regions (Marinelli et al., 2024; Marinelli et al., 2025). Our study extends these assessments by evaluating the progression of groundwater sustainability through 2100 at monthly resolution, thereby moving beyond a simple assessment of whether sustainability thresholds are exceeded and incorporating the frequency, severity, duration, and timing of threshold exceedance into our groundwater sustainability assessment. These contributions are crucial for informed management of groundwater systems, as our results demonstrate that groundwater sustainability is a highly dynamic process that requires both short-term and long-term considerations by decision makers.

Several of the major hotspots we identify, such as the Indo-Gangetic Plain, North China Plain, Central Valley, and High Plains, have been highlighted repeatedly in previous studies of groundwater depletion and groundwater stress. Furthermore, each of

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these regions is considered both an ecological and a social hotspot of water stress (Huggins et al., 2022), highlighting the urgency of adaptive and mitigative measures to reduce future impacts. The persistence of these hotspots across historic and future assessments suggests that the underlying drivers of groundwater unsustainability remain largely unchanged. High groundwater demands, extensive irrigated agriculture, and hydrogeological conditions that limit rapid recovery continue to place substantial pressure on these systems, with increasing risks over time unless effective adaptation and mitigation measures are implemented. While these drivers may also contribute to the emergence of new hotspots in vulnerable regions, such as around the Mediterranean Sea or in the Sahel (e.g., Marinelli et al., 2025; Rohde et al., 2024), our results primarily indicate the persistence and intensification of existing groundwater sustainability challenges in many of the most heavily exploited aquifers globally.

The temporally explicit framework adopted here also reveals characteristics of groundwater sustainability that cannot be captured by threshold exceedance analyses alone. While de Graaf et al. (2019) and Marinelli et al. (2025) focused primarily on identifying whether and when environmental limits are exceeded and the degree to which long-term historic groundwater use was unsustainable, our results demonstrate how groundwater unsustainability evolves through time. Aquifers may experience frequent but relatively minor departures from sustainable conditions, prolonged periods of severe unsustainability, or even recovery under favorable hydroclimatic conditions. Moreover, the pronounced seasonal and inter-annual patterns identified in many aquifers demonstrate that groundwater sustainability cannot always be adequately represented by long-term averages or single exceedance events. Our findings reinforce the importance of considering frequency, severity, timing, and duration when evaluating groundwater sustainability (Marinelli et al., 2024; Marinelli et al., 2025). By taking these metrics into account, our assessment provides a more comprehensive characterization of future groundwater sustainability risks.

4.3 Model performance, uncertainty, and limitations

The strong agreement between simulated groundwater head and withdrawals and the observed and reported values indicates that the coupled VIC-WUR-MODFLOW framework accurately reproduces the large-scale dynamics governing global groundwater sustainability. This supports our interpretation of projected groundwater sustainability patterns and their associated severity. The validation of groundwater heads is particularly important because simulated head is the primary indicator used to assess groundwater sustainability in this study. Agreement between the simulated and observed groundwater head suggests that the model adequately captures the balance between groundwater recharge, discharge, and abstraction processes that control groundwater storage dynamics.

The improved simulation of river low-flows following the inclusion of the groundwater discharge forcing in VIC-WUR further suggests that the model adequately represents groundwater contributions to streamflow (Liu et al., 2026). This indicates that groundwater discharge plays an important role in sustaining simulated low-flows in surface water systems. Given that our

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sustainable groundwater thresholds are derived from environmental flow requirements, accurately capturing the groundwater discharge to surface water systems is essential. The improvement seen in the river discharge validation therefore increases confidence that the sustainability thresholds applied in this study represent realistic hydrogeological conditions.

The strong agreement between simulated surface water and freshwater withdrawals further supports the ability of the model to represent large-scale water use dynamics. The model performance should, however, be interpreted at the model resolution (5-arcmin and monthly timesteps), as our findings represent hydrogeological conditions at these resolutions and under the projected climate and water use conditions considered in this study. Consequently, the results are primarily intended to indicate large-scale patterns of projected groundwater sustainability rather than precise local predictions. Nevertheless, the ability of the model to reproduce observed and reported large-scale groundwater behavior supports its suitability for global groundwater sustainability assessments.

A potential source of model uncertainty arises from the transition between the historic period forced by WFDE5 climate data (Cucchi et al., 2020) and the current and future periods forced by bias-adjusted GFDL climate projections (Lange and Büchner, 2021). The abrupt change in forcing datasets can introduce artificial discontinuities if there are sudden discrepancies in the fluxes entering and leaving the groundwater system. To minimize these effects, we incorporated the current period (2015-2025) prior to the future analysis period (2026-2100) to act as a buffer once the climate forcing changed. By giving the model additional time to stabilize, and also calculating sustainable groundwater thresholds using 60-month moving windows, we aimed to ensure that our estimates of groundwater sustainability reflect projected hydrogeological changes rather than short-term fluctuations or artifacts associated with the forcing transition.

Several sources of uncertainty should also be considered when interpreting the results of this study. First, due to computational limitations, future projections were generated using a single climate model. Although the selected GFDL model was chosen following the ISIMIP3b protocol and is considered representative of an average climate response among global climate models (Lange, 2021), a single model does not capture the full range of uncertainty associated with future climate projections. Different climate models may produce different precipitation, evapotranspiration, and recharge responses in some regions, which would propagate into groundwater sustainability estimates. Future studies could address this limitation through multi-model ensemble approaches that quantify the sensitivity of groundwater sustainability to climate model selection. Such approaches would also help assess the robustness of the relatively small differences observed between SSP1-2.6 and SSP3-7.0 scenarios.

Additional uncertainty arises from assumptions regarding future water use. Several datasets used to estimate water demands were held constant beyond 2015 or relied on static spatial distributions. Domestic and industrial freshwater demands from 2015-2100 were spatially downscaled using a fixed population density map from 2015 (CIESIN, 2017). While this approach

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provides a realistic estimate of the concentrations of demands, it also assumes no urban expansion through the end of the century. Livestock demands from 2015-2100 were calculated using static animals counts from 2015 (FAO, 2026b), meaning the demands only fluctuate as a function of air temperature and do not account for changes in the distribution of livestock. Total pumping capacities per hydrological unit remained static beyond 2015 (Sutanudjaja et al., 2018). While the spatial distribution of pumping capacities was dynamic as a function of groundwater demands, this approach assumes no increases in pumping capacity due to technological development or decreases due to policy interventions. Lastly, crop coverage was based on four reference years (2000, 2005, 2010, 2015). While we interpolated the data between these reference years, we held the 2000 and 2015 values static when backcasting to 1979 and forecasting to 2100. This approach assumes no agricultural expansion through the end of the century, nor does it account for improvements in irrigation efficiency or adjustments in crop selection, although the irrigation demands do fluctuate with changes in climate. Together, these assumptions limit the representation of future changes in water management and water demand, and may therefore influence the spatial and temporal patterns of projected groundwater sustainability. Incorporating dynamic datasets accounting for changes to population, livestock, pumping capacities, and crop coverage would increase the robustness of the model results, and, therefore, provide more realistic assessments of groundwater sustainability. Such updates to the input datasets should become possible by following the forthcoming ISIMIP 4 protocol.

The sustainability framework itself also contains conceptual limitations. Sustainable groundwater head thresholds are derived from environmental flow considerations and therefore focus specifically on groundwater-surface water interactions. While this approach provides a physically and ecologically relevant indicator of groundwater sustainability, it does not capture all dimensions of sustainable groundwater management. Groundwater quality, land subsidence, seawater intrusion, social water-security concerns, and economic impacts are all dimensions of groundwater sustainability that could be incorporated to provide a more comprehensive assessment of projected groundwater sustainability.

Taken together, these uncertainties do not substantially alter the central conclusions of this study. Across a wide range of hydroclimatic settings, groundwater sustainability thresholds are projected to be exceeded frequently through the end of the century, with the most severe impacts concentrated in a limited number of hotspots. Future research should aim to reduce uncertainties in groundwater sustainability assessments by incorporating projections from multiple climate models, thereby better capturing climate uncertainty. Such analyses would become increasingly refined with continued improvements in computational efficiency, including faster model runtimes and more efficient data handling to enable large ensemble simulations. Additional advances could include representing dynamic water use and management strategies, incorporating future socio-economic development pathways, and extending assessments to explicitly evaluate ecological impacts. Together, these developments would provide more robust and comprehensive assessments of future groundwater sustainability.

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5 Conclusion

This study projected the evolution of global groundwater sustainability through 2100 using a coupled VIC-WUR-MODFLOW modelling framework forced with future climate and water use scenarios. By extending previous groundwater sustainability assessments beyond the use of long-term historic averages and the identification of initial threshold exceedance, we projected the frequency, severity, timing, and duration of environmentally unsustainable groundwater use at monthly temporal resolution. This dynamic approach demonstrates that groundwater sustainability is not a binary condition, but a process characterized by recurring periods of unsustainable conditions, recovery, and decadal trends.

Our results indicate that environmentally unsustainable groundwater use will be widespread throughout the 21st century, with groundwater head projected to fall below sustainable thresholds in 89% of evaluated gridcells at least once during the simulated period due to anthropogenic groundwater demands. Although this unsustainable groundwater use is geographically extensive, its severity is largely concentrated within a few hotspot regions, including the Indo-Gangetic Plain, North China Plain, Central Valley, and High Plains. Temporal analyses further reveal that groundwater unsustainability is projected to intensify towards the end of the century and exhibits pronounced seasonal variability in many aquifers. The differences in projected groundwater sustainability between the SSP1-2.6 and SSP3-7.0 scenarios are more evident in the severity than frequency of unsustainable conditions, suggesting that, due to differences in hydroclimatic conditions and water demand, future climate and socioeconomic pathways may primarily influence the degree of groundwater overexploitation rather than its occurrence.

These findings emphasize the importance of evaluating groundwater sustainability at temporal resolutions capable of resolving seasonal and inter-annual dynamics. Assessments based solely on long-term averages or first threshold exceedance cannot capture the recurrence, persistence, or recovery of groundwater systems, all of which influence the environmental impacts of groundwater abstractions. By integrating environmentally derived groundwater sustainability thresholds with transient groundwater simulations, this study provides a comprehensive framework for assessing future groundwater sustainability under changing climate and anthropogenic water use conditions. Future research can take this approach further by assessing the projected environmental and anthropogenic implications of alternative groundwater management strategies.

As climate change, population growth, and economic development continue to drive increasing water demands, thereby increasing the pressure on groundwater resources as the largest global store of accessible freshwater, understanding how groundwater sustainability evolves through time is crucial for protecting groundwater-dependent ecosystems and maintaining freshwater resources in a sustainable future. The modelling framework presented here provides a globally consistent basis for identifying regions most vulnerable to future groundwater overexploitation and offers a foundation for evaluating future groundwater management and adaptation strategies aimed at reducing long-term environmental impacts caused by human activities.

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Appendix

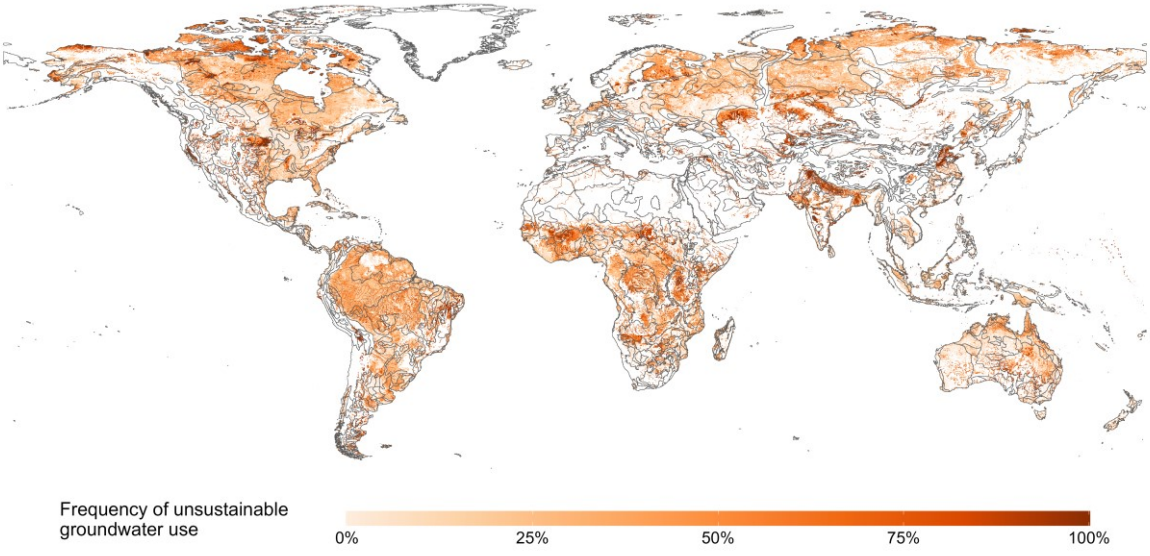

Figure A1: Mean unsustainable frequency of groundwater use from 2026-2100 under the SSP1-2.6 future scenario. A value of 0% indicates groundwater use is never projected to be unsustainable, a value of 50% indicates groundwater use is projected to be unsustainable in half of all timesteps, a value of 100% indicates groundwater use is always projected to be unsustainable.

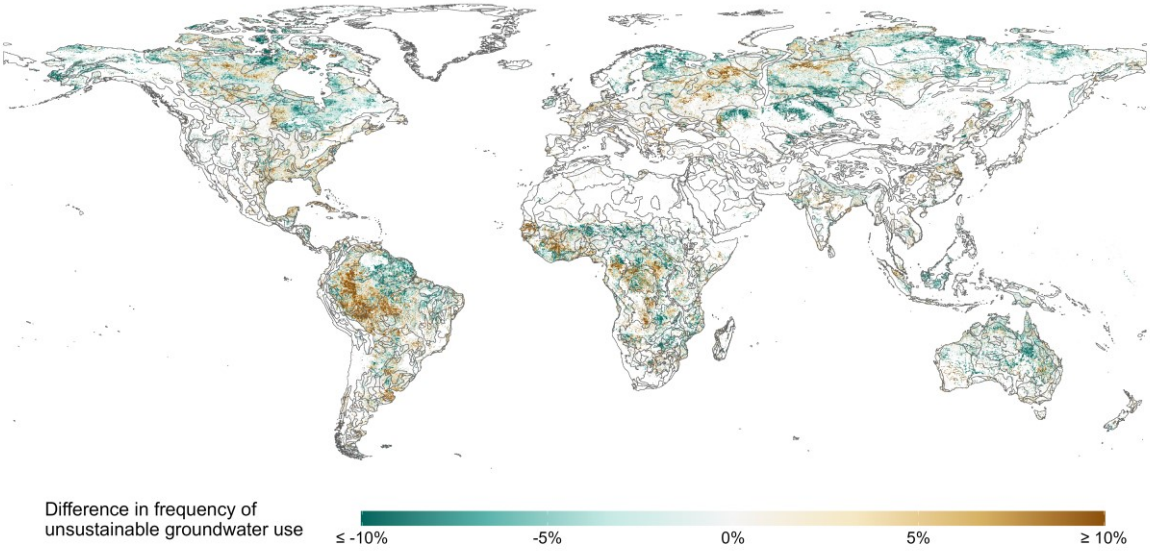

Figure A2: Difference in mean unsustainable frequency of groundwater use from 2026-2100 between the SSP3-7.0 and SSP1-2.6 future scenarios. Brown gridcells indicate groundwater unsustainability will be more frequent under the SSP3-7.0 scenario, green gridcells indicate groundwater unsustainability will be more frequent under the SSP1-2.6 scenario.

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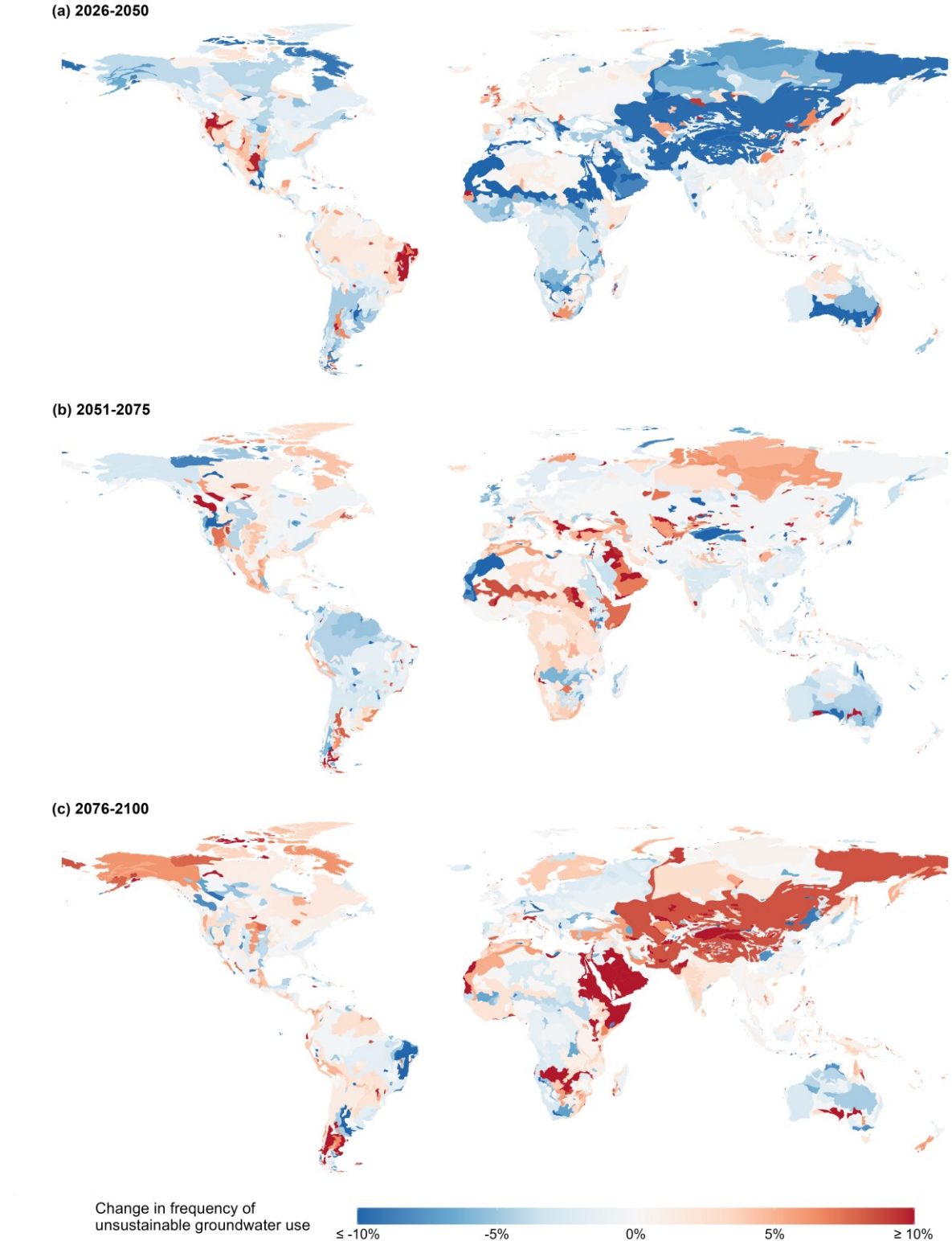

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Figure A3: Difference in unsustainable frequency of groundwater use over 25-year intervals from 2026-2100, when compared to the mean over the full future period, for the SSP1-2.6 scenario. Results are aggregated over aquifer extents. Red aquifers indicate the unsustainable frequency in that specific time period will be more frequent than the mean over the full period, while blue aquifers indicate the unsustainable frequency in that specific time period will be less frequent than the mean over the full period.

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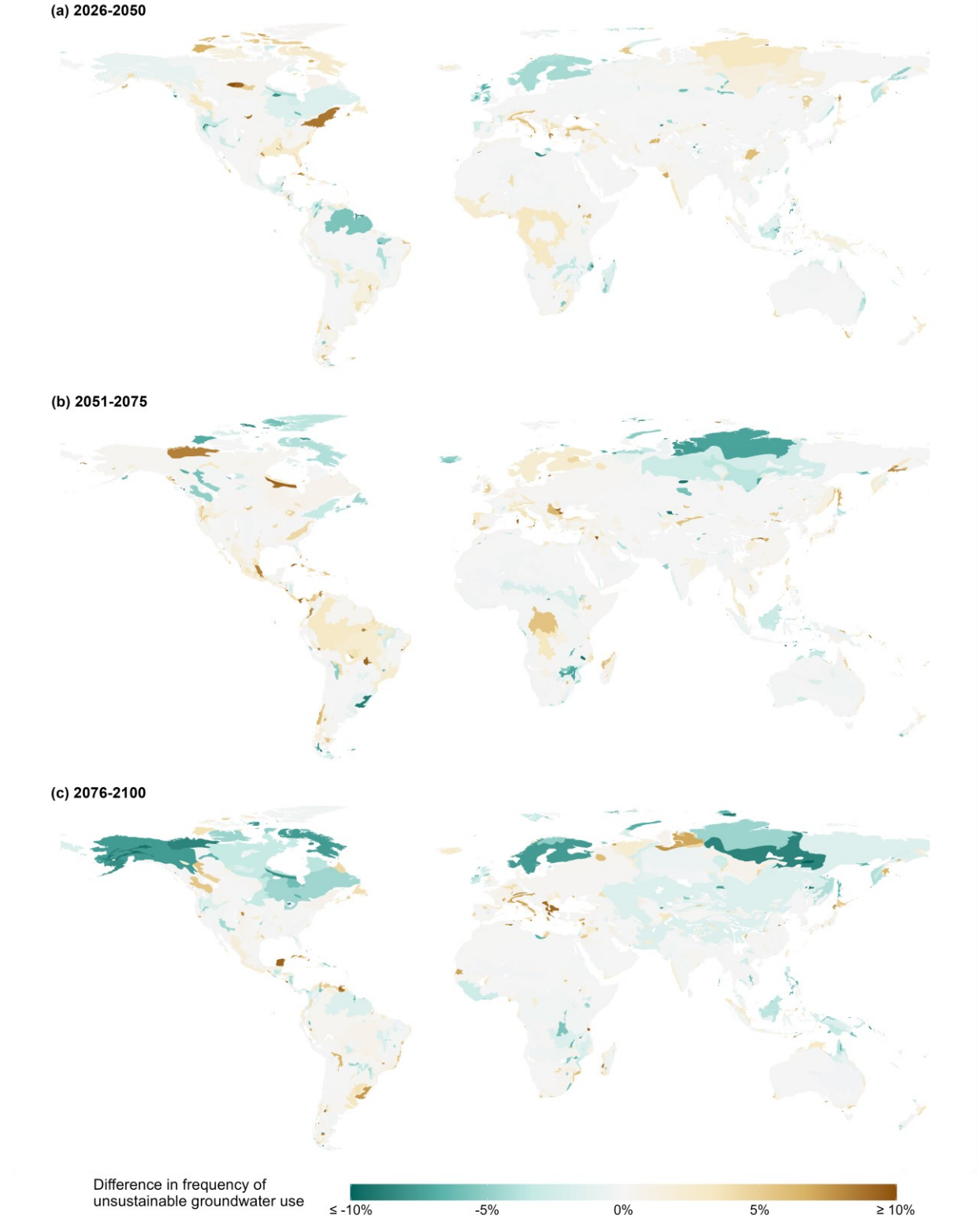

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Figure A4: Difference in mean unsustainable frequency of groundwater use from 2026-2100 between the SSP3-7.0 and SSP1-2.6 future scenarios. Results are aggregated over aquifer extents. Brown gridcells indicate groundwater unsustainability will be more frequent under the SSP3-7.0 scenario, green gridcells indicate groundwater unsustainability will be more frequent under the SSP1-2.6 scenario.

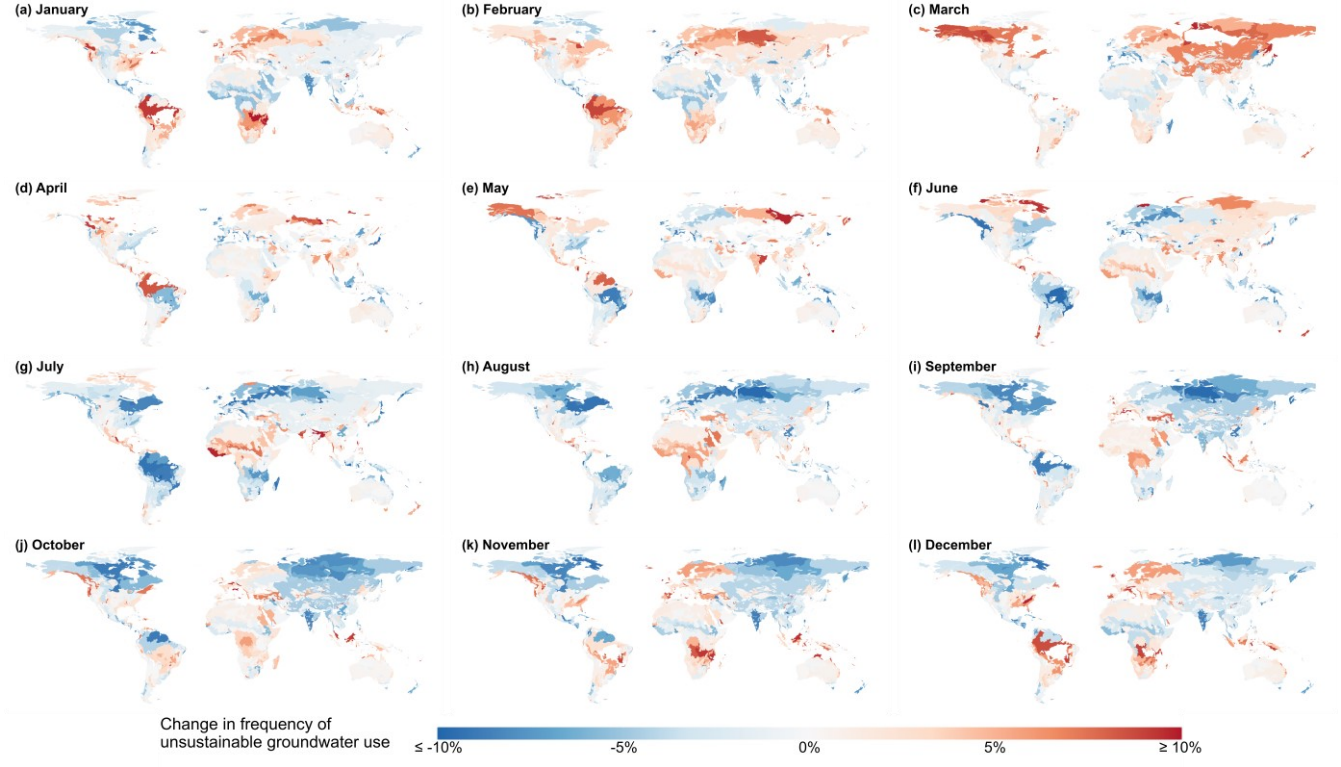

Figure A5: Difference in mean unsustainable frequency of groundwater use per month from 2026-2100, when compared to the mean over the full future period, for the SSP3-7.0 scenario. Results are aggregated over aquifer extents. Red aquifers indicate the unsustainable frequency in that month will be more frequent than the mean over the full period, while blue aquifers indicate the unsustainable frequency in that month will be less frequent than the mean over the full period.

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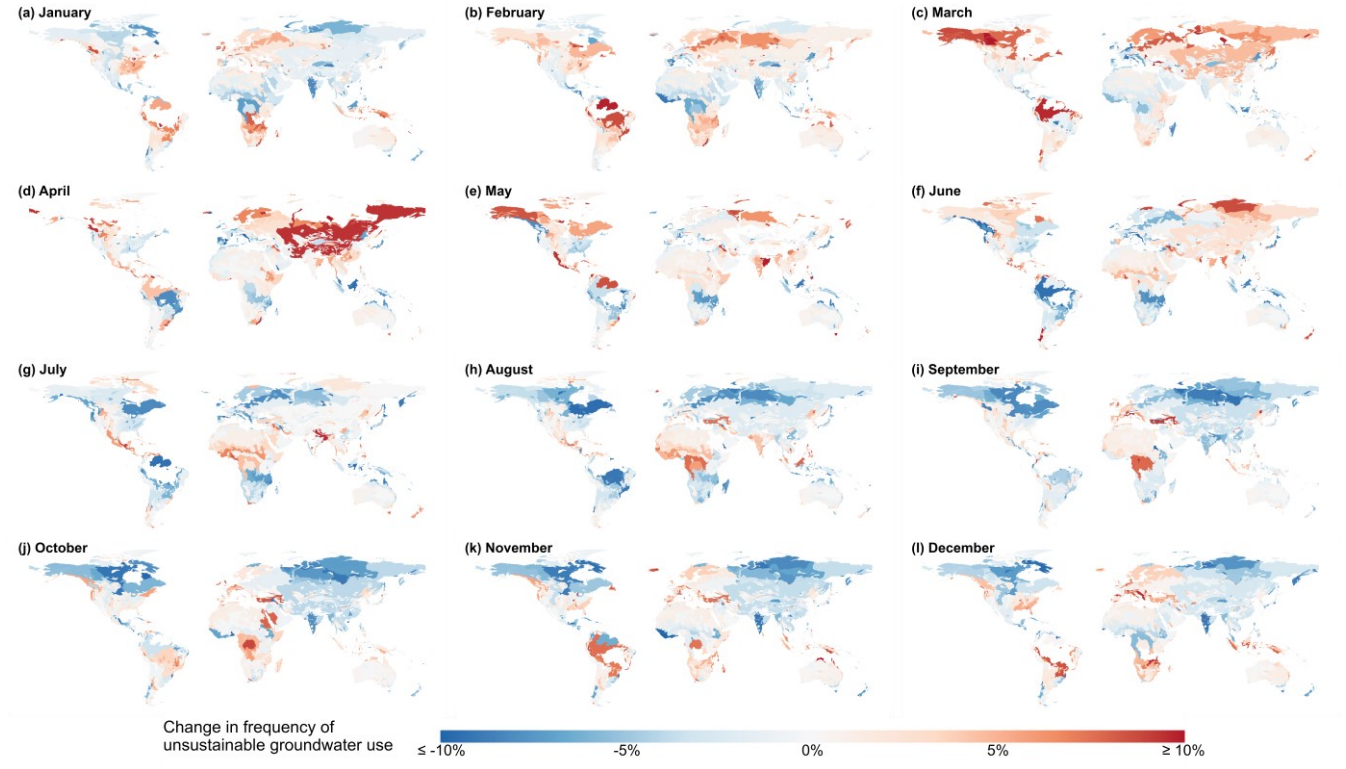

Figure A6: Difference in mean unsustainable frequency of groundwater use per month from 2026-2100, when compared to the mean over the full future period, for the SSP1-2.6 scenario. Results are aggregated over aquifer extents. Red aquifers indicate the unsustainable frequency in that month will be more frequent than the mean over the full period, while blue aquifers indicate the unsustainable frequency in that month will be less frequent than the mean over the full period.

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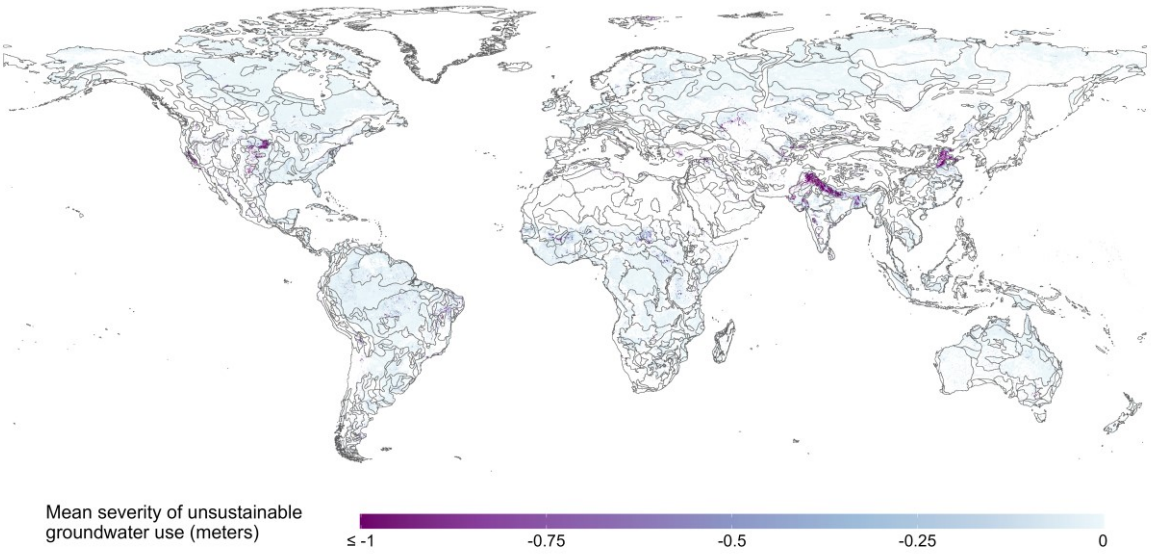

Figure A7: Mean unsustainable severity of groundwater use from 2026-2100 under the SSP1-2.6 future scenario. Negative values indicate how far below the sustainable threshold the groundwater head is projected to be.

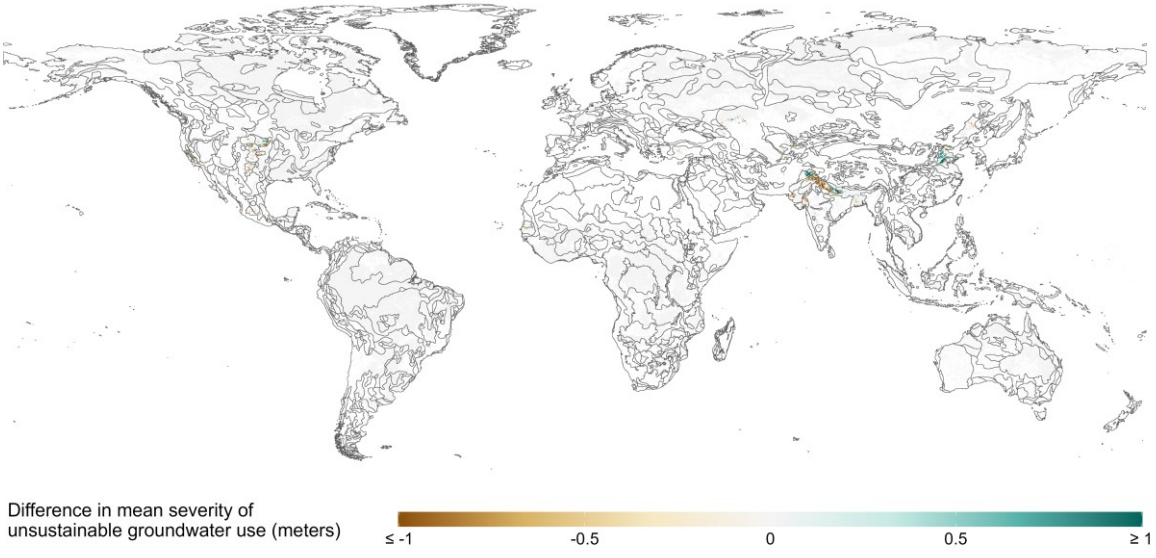

Figure A8: Difference in mean unsustainable severity of groundwater use from 2026-2100 between the SSP3-7.0 and SSP1-2.6 future scenarios. Brown gridcells indicate groundwater unsustainability will be more severe under the SSP3-7.0 scenario, green gridcells indicate groundwater unsustainability will be more severe under the SSP1-2.6 scenario.

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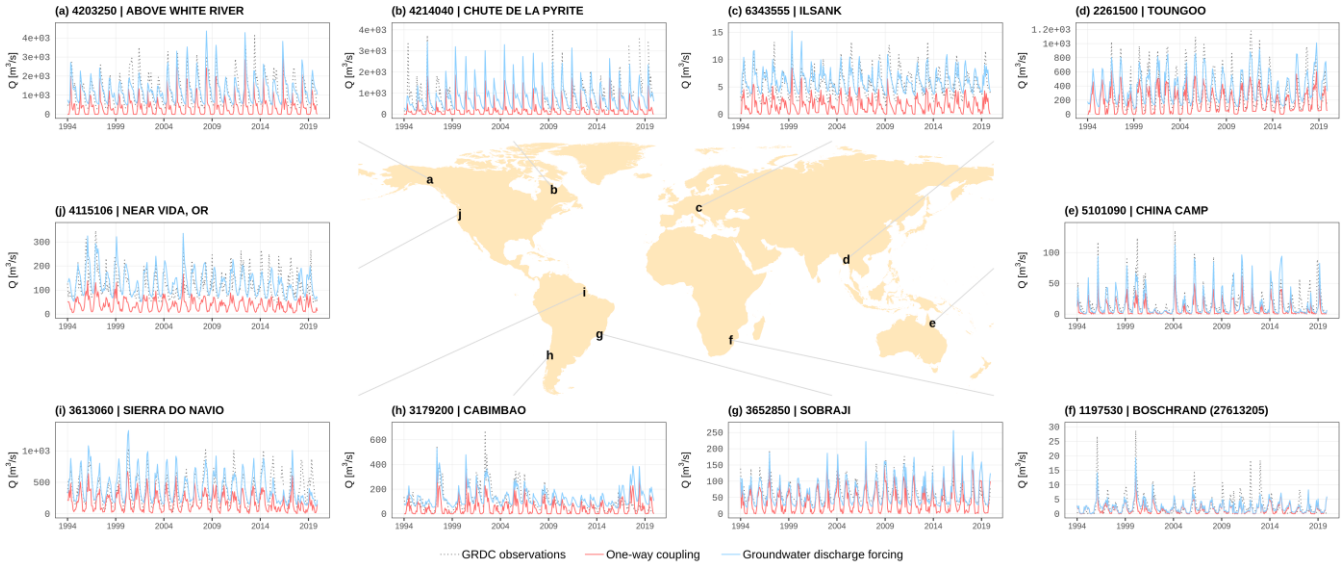

Figure A9: River discharge validation for select gauging stations (including GRDC station IDs) indicating the influence of forcing VIC-WUR with groundwater discharge. The blue and red lines represent the simulated VIC-WUR river discharge with and without the groundwater discharge forcing, respectively. The simulated results are from the SSP3-7.0 human-impacted run.

Data availability

Data necessary to evaluate the findings of this study will be made publicly available upon acceptance of the manuscript at: https://doi.org/10.4121/c1b643f5-af94-4dc4-a80e-a5b0cd56f955.

Author contribution

BM and IG conceptualized the study. BM and SL curated the data. BM performed the formal analysis. IG acquired the funding. BM, SL, and KD conducted the investigation. BM and SL developed the methodology. AW and IG administered the project and supervised the research. BM, SL, and KD developed the software and validated the results. BM and KD prepared the visualizations. BM prepared the original draft of the manuscript. All authors contributed to reviewing and editing the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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