https://doi.org/10.5194/egusphere-2026-5142
Preprint. Discussion started: 15 September 2026

Long-Term Assessment of Groundwater Recharge in the Amalie Lany Aquifer, the Czech Republic, from 1990 to 2089

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Abstract

The influence of climate change on groundwater levels and recharge remains insufficiently quantified, particularly in low-precipitation regions where groundwater is a critical water-supply source. In the Czech Republic, groundwater abstraction for public supply reached 366 million m^3 between 1990 and 2020. Over the same period, the Amálie Lány site in Central Bohemia experienced warming, with maximum air temperature increasing by 1.1–1.5 °C and minimum air temperature by approximately 1 °C, accompanied by a slight decrease in mean annual precipitation of about 50 mm. These hydroclimatic shifts can intensify drought by increasing atmospheric water demand and altering soil moisture, infiltration, groundwater recharge, and water-table dynamics.

This research estimates long-term groundwater recharge (1990–2089) using a physically based framework that couples the Richards equation with heat transport and an energy-balance top boundary to represent liquid, vapour, and heat fluxes, including phase change. The analysis targets an unconfined carbonate aquifer system in western Central Bohemia, where infiltration is the dominant recharge mechanism. Forcing data combine ERA5 hourly meteorology and local observations (1990–2020) with climate projections (1990–2089) under four Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) using precipitation, temperature, wind speed, cloud cover, solar radiation, and relative humidity.

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Recharge was simulated with the Richards equation in the open-source DRUtES platform using coupled liquid, vapour, and heat transport. The model represents two observation boreholes within compacted sedimentary layers underlain by fractured formations and incorporates key hydraulic and thermal parameters (van Genuchten properties, anisotropy, thermal conductivity, and root-zone characteristics). Results are reported per decade averages across observation points in the soil profile.

Recharge trajectories diverge markedly between scenarios. Under SSP1-2.6, recharge remains relatively stable, whereas higher-emission pathways produce a sustained decline, reaching reductions of up to 50% by late century under SSP5-8.5. The findings highlight precipitation and atmospheric demand as dominant controls on recharge and underscore risks to water security under continued warming.

Keywords: Groundwater, Climate change, Evaporation, Precipitation, Temperature, Eras5

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1. Introduction

Groundwater is a crucial natural resource that sustains many life forms and has significantly contributed to advancing human civilisation Simlandy (2015). As a primary source of freshwater, it meets the needs of a large portion of the global population, alongside supporting industries and ecosystems Al Atawneh et al. (2021). Groundwater recharge (GWR) plays a vital role in maintaining the sustainability and hydrological equilibrium of subsurface water systems Al Atawneh et al. (2021); Döll and Fiedler (2008); Thampi and Raneesh (2012). GWR is the process through which surface water infiltrates the soil and percolates into aquifers, replenishing subsurface water reserves. This recharge occurs either via direct infiltration of precipitation or through the seepage of water from nearby surface water bodies, such as lakes and rivers Al Atawneh et al. (2021).

Groundwater comprises approximately 96% of the unfrozen freshwater reserves on the Earth Amanambu et al. (2020); Taylor et al. (2013); Wada (2016) and contributes to 33% of global total water withdrawals Famiglietti (2014); Siebert et al. (2010). Consequently, there is increasing concern and

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focused research on the effects of climate change on groundwater resources Green et al. (2011); Kundzewicz and Doell (2009); Taylor et al. (2013), as changes in precipitation, temperature, evaporation, and other climatic variables pose significant challenges to groundwater sustainability. The rate and extent of GWR are largely governed by atmospheric conditions, including precipitation, temperature, and evaporation rates, as well as soil properties that influence water movement through pore spaces. Consequently, changes in global climate patterns can substantially affect groundwater availability and quality, as variations in precipitation or heightened evaporation rates may alter recharge rates, potentially threatening groundwater sustainability Chambel (2015); Sowers et al. (2011). A thorough understanding of these processes is essential for effective groundwater management in the context of climate change.

According to Cárdenas Castillero et al. (2021), reductions in aquifer recharge due to climate change's effects, with projected future decreases have been estimated by authors such as Orehova and Bojilova (2001), Candela et al. (2009), Guardiola-Albert and Jackson (2011), Stigter et al. (2014), Touhami et al. (2015), Moutahir et al. (2017), Chavarría and Vargas (2018), Lauffenburger et al. (2018), Moutahir et al. (2019), Haidu and Nistor (2020), Costa et al. (2021), and Swain et al. (2022) have highlighted this diminishing recharge trend. In contrast, some regions—particularly those dominated by winter snow—may experience aquifer overcharge due to increased melting, as shown by Uribe et al. (2003), Scibek and Allen (2006), Jyrkama and Sykes (2007), Newcomer et al. (2014), Serur (2020), and Wöhling et al. (2020). This variability underscores climate change's complex and region-specific impacts on groundwater recharge patterns.

Due to the impacts of climate variability and climate change on hydrogeological resources, there is a need to improve our understanding of groundwater vulnerability and to develop appropriate water management and adaptation strategies. In this context, the main objective of this study is to quantify the impact of climate change on long-term groundwater recharge in the Amalia Lány watershed, located near the village of Lány in Central Bohemia, Czech Republic. The working hypothesis is that, under ongoing climate change, evaporation in the Amalia Lány watershed will increase, while groundwater recharge will decline as a result of higher atmospheric demand and altered precipitation patterns. The magnitude of these changes is quantified by cou-

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pling a soil–hydrodynamic model with boundary conditions from the climate model.

The Amalia Lány watershed was selected because it has been the focus of several field research projects conducted by the Czech University of Life Sciences Prague (CZU), particularly those measuring soil properties that are essential for groundwater modelling and analysis. To estimate groundwater recharge in Lány, two soil profiles of different depths were defined. Physical soil data were obtained from multiple sources: volumetric water content in the upper 20 cm was measured in situ by researchers from the Department of Environmental Modelling, while hydraulic and textural properties for the deeper layers were compiled from bibliographic and database sources.

Climate data used as input to the model were provided by the Czech Hydrometeorological Institute and were employed to construct a baseline of climatic conditions and to model the groundwater recharge for the period 1990–2019. Subsequently, output from global climate models was downscaled to the Lány region and used as a boundary condition to model recharge over 100 years. To characterise the variability and impact of climate change, recharge and evaporation anomalies were computed relative to the historical baseline and compared with findings from other studies in Central Europe, where groundwater is known to be highly sensitive to future climate variability.

This paper is organized as follows. Section 1 reviews the current state of knowledge on groundwater recharge under climate change and summarises key findings from previous studies. Then the study area (section 2) described the location, soil profiles and Amalie Lany geology. The Methodology section 3 describes the sources of physical, historical and synthetic climate data; the global climate models used; the DRUtES model and its constitutive relations following Saito et al. (2006) and Sakai et al. (2011); the numerical setup for recharge simulations; and the estimation of soil parameters. The Results and discussion section 4 presents, in turn, groundwater recharge for 1990–2020, the projected impact of climate change on recharge up to 2090, and long-term evaporation. Finally, the Conclusions 5 synthesise the main insights on how climate variability and change affect groundwater recharge in this watershed.

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2. Study Area

The study area is in Amalie Lány, an agricultural region of Central Bohemia, western Czech Republic (Figure 1). The area is 7.72 km^2 and is characterised by a gentle topography with elevations ranging from sea level from 345 to 475 m a.s.l. The region encompasses the mountainous sub-catchments draining into the reservoir of Udolhi Nadrz Kicova. Soils within the study area are classified as loam-clay and clay. The natural availability of water resources is dominated by the prevailing temperate continental climate/humid continental climate according to the Köppen classification. Figure 1 shows the location of the Amalia Lány watershed.

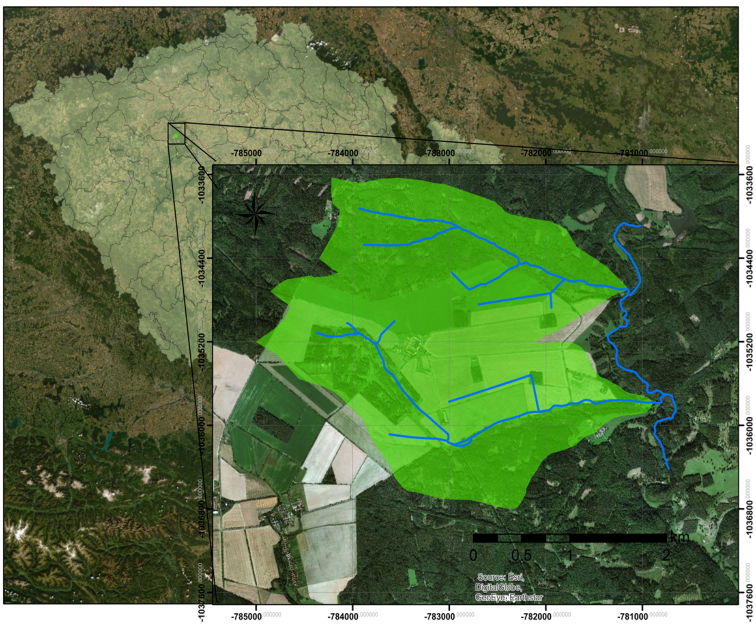

Figure 1: Location of Amalia Lány Watershed. Sources: Esri, Maxar, Earthstar Geographics, and the GIS User Community | Powered by Esri.

The Amalia Lány aquifer consists of 25-metre-thick fractured permo-carbon sedimentary rock sequences belonging to the Berounka basin. The groundwater flow is related to a fissured system of the Algonkian age, which is

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integrated by weathering, tectonic faults, and material deposits. The aquifer layer is also based on Permocarbon and Mesozoic layers. These layers form a structure within the system with a significant water supply Kahuda (2021).

The area comprises over twenty study and observation boreholes (see Figure 2). Two boreholes (since now soil profile) have been selected for this investigation. The selected soil profile are wells BP-I/1 and wells BP-1/3. For the soil infiltration model, the piezometric level is assumed to be 4 meters deep for the soil profile BP-I/1 and at -2 meters for the soil profile BP-I/3. It is important to note that the rainfall transformation into the groundwater recharge by the evapotranspiration loss (surface and subsurface evaporation and root after uptake), which takes place continuously over the entire soil profile and is governed by the meteorological events represented here as a time-dependent surface boundary condition. Figure 2 shows the selected soil profiles (boreholes).

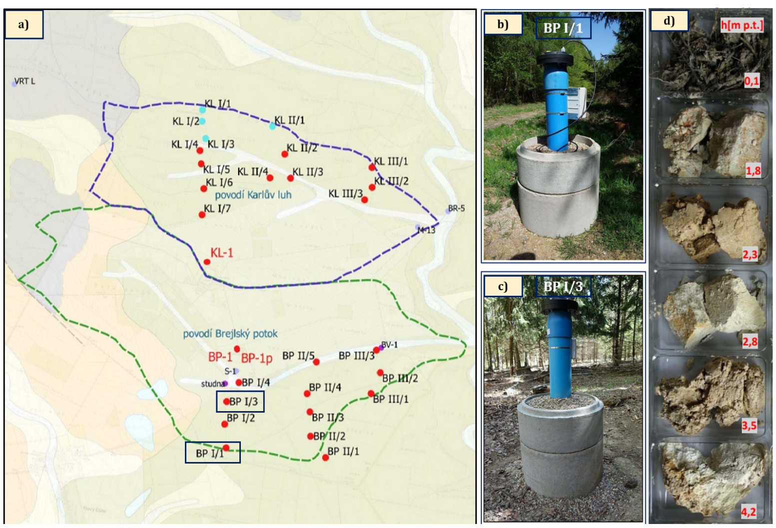

Figure 2: Location of boreholes selected for study. a) Shows all boreholes (soil profile) on the Amalia Lány watershed, b) Photo of sensors and location of soil profile BP-I/1, c) Photo of sensors and location of soil profile BP-I/3, d) Soil profile samples. From top to bottom, the soil profile is comprised of organic material, clay-sand, loam to marl, clayey; hard-clay, and angular fragments of argillaceous rocks. Sources: Esri | Powered by Esri

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2.1. Geological Description

Amalia's geological surface is based on the slate Neoproterozoic. These slates are composed of the Blovice Formation, which is composed of fine and medium-sized debris, slate, and siltstones [$_{W}$NP^{bl}], delicate and medium-grained offal with clastic mica [W^{sl}NP$_{bl}$], and coarse-grained offal [W^{h}NP$_{bl}$]. The Neoproterozoic belongs to the geological scale of the last era of the Pre-cambrian Supereon and the Proterozoic Eon. The Holocene and Pleistocene deposits form the deepest part of the basin (where the streams Karl and Brejl flow). The banks of the streams are covered by flush clayey and sandy loam, places with rock fragments [Q^{h}], fluvial clays, sands, scraps [^{f}Qh], and sediments of water reservoirs [^{n}Q]. Pleistocene deposits on river banks consist of clay and fragmented rocks [$^{s}_{hj}$ Q]. A fault crosses the north section of the basin from the west to the northeast. The entire west part of the study area presents well-identified faults, which separate the Palaeozoic Carboniferous Pennsylvania group from the Proterozoic Neoproterozoic Cryogenian group.

Toward the northwest, the geology belongs to the Palaeozoic Carboniferous Pennsylvania group, composed of sandstones, siltstones, clay-stones, conglomerates, volcaniclastics, and coal seams [Cr$_{2}$] belonging to the Kladno formation. In the basin's centre, Quaternary-Holocene denudation [^{a}Q] (anthropogenic deposits like heaps, landfills, and loops) are located. On the northeast limits, deposits from the upper Pleistocene are identified; these deposits consist of sandy clay and clay with rock fragments [^{e}sQp^{3}]. Toward the southwest, spilitized basalt [βNPbl] belonging to the Neoproterozoic group predominates. To the south, in the upper topographic limits of the basin, a classified formation of the Neogene period is identified. This geological structure is formed by rocks of silicon and quartz [sN].

3. Methodology

In this section, the methods used to simulate soil–water dynamics and to assess the impacts of climate change on groundwater recharge and evaporation are described. The methodological framework combines a one-dimensional soil hydrodynamic model with historical and climate model boundary conditions to quantify long-term trends and assess the validity of the working hypotheses.

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The Methodology section is structured as follows. Section 3.1 presents the hydrodynamical model, including its formulation, boundary conditions and initial conditions. Section 3.2 describes the simulation periods considered, distinguishing the historical baseline from the future climate projections. Section 3.3 defines the indicators used to analyse changes in groundwater recharge and evaporation and to evaluate the hypotheses formulated in section 1.

3.1. Hydrodynamical Models

Recharge simulations have been performed with DRUtES open software Kuráž and Mayer (2013). DRUtES solves the governing equations in 1/2/3 spatial dimensions using the finite element method. In this contribution, the model for movement of water in variably saturated conditions was described by Saito et al. (2006); Sakai et al. (2011) model that couples the transport of water in the liquid and vapour phases with the transport of heat. DRUtES integrates meteorological conditions as boundary conditions, root water uptake using Feddes et al. (1978). In this research, the soil hydraulics properties (SHP) are parametrised with the frequently used Mualem-van Genuchten model van Genuchten (1980); Mualem (1976). The presence of snow and freezing was neglected for this model infiltration. Figure 3 shows a comprehensive modelling system for estimating groundwater recharge by integrating climate dynamics, soil properties, and advanced numerical simulations.

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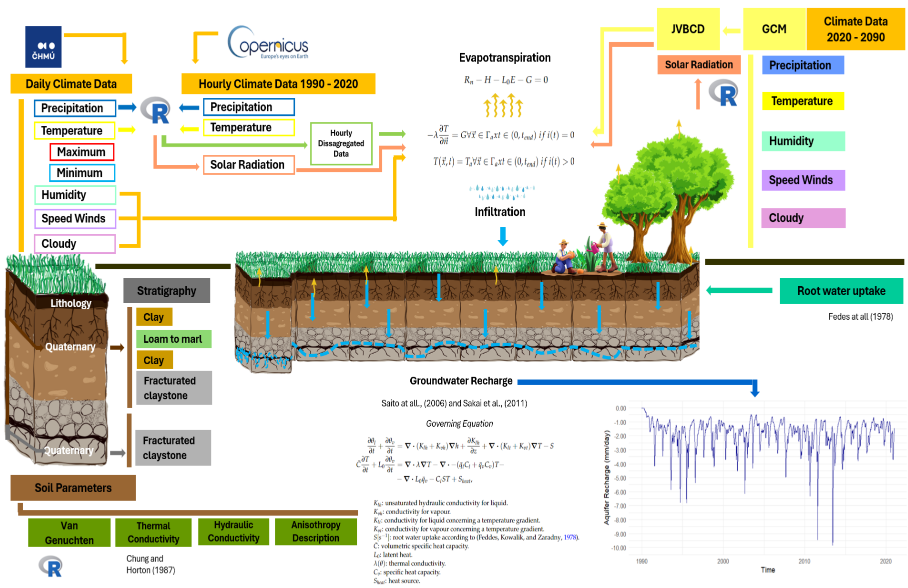

Figure 3: Integrated Modelling Framework for Groundwater Recharge Using Climate Data, Soil Properties, and Energy Balance Dynamics. Own elaboration.

Figure 3 illustrates a conceptual framework for modelling groundwater recharge, integrating climate data, soil properties, and governing equations. The input of climate data incorporates historical and future climate data. Hourly climate data from 1990 to 2020 are sourced from Copernicus and disaggregated from daily measurements, covering variables such as precipitation, temperature (maximum and minimum), humidity, wind speed, cloud cover, and solar radiation. Future projections for 2020 to 2090 are derived from GCMs under various scenarios, including the same variables to assess climate-driven impacts.

The Saito et al. (2006); Sakai et al. (2011) model (see equations below) is a coupled model; the solution is constituted by two independent variables, pressure head h [L] and temperature T. It further defines constitutive relations for the liquid and vapour water contents, and using derived flux equations, it further describes water, vapour and heat fluxes. The top boundary condition is defined by the surface energy balance equation. The Saito et al.

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(2006); Sakai et al. (2011) are represented in the equations below:

$$\frac{\partial \theta_l}{\partial t} + \frac{\partial \theta_v}{\partial t} = \nabla \cdot [(K_{lh} + K_{vh}) \nabla h] + \frac{\partial K_{lh}}{\partial z} + \nabla \cdot [(K_{lt} + K_{vt}) \nabla T] - S, \quad (1)$$

$$C \frac{\partial T}{\partial t} + L_0 \frac{\partial \theta_v}{\partial t} = \nabla \cdot (\lambda \nabla T) - \nabla \cdot [(\bar{q}_l C_l + \bar{q}_v C_v) T] - \nabla \cdot (L_0 \bar{q}_v) - C_l S T + S_{\text{heat}}. \quad (2)$$

where:
K_{lh}: unsaturated hydraulic conductivity of the liquid phase;
K_{vh}: vapour-phase conductivity;
K_{lt}: liquid-phase thermal coupling coefficient (flow driven by a temperature gradient);
K_{vt}: vapour-phase thermal coupling coefficient;
S: root water uptake sink term;
C: volumetric heat capacity;
L_0: latent heat of vaporization;
$\lambda(\theta)$: thermal conductivity;
C_l: specific heat capacity of liquid water;
S_{heat}: external heat source.

3.1.1. Domain setup

The rainfall/evaporation transformation into groundwater recharge is represented here by two soil profiles. We employ here one-dimensional modeling. The depth of the first soil profile (BP-1-1) was 4 m, and the depth of second soil profile (BP-1-3) was 2 m. The domain was nonuniformly discretized with a step size of 1 mm near the surface and 10 cm near the bottom boundary. The time-step was adaptively changing between fractions of seconds to 200 s following the methodology proposed by Kuráž et al. (2010). The governing equations were integrated using the linear finite element method, details in Kuráž and Mayer (2013); Kuraz et al. (2013). Figure 4 represents the domain setup for both soil profiles.

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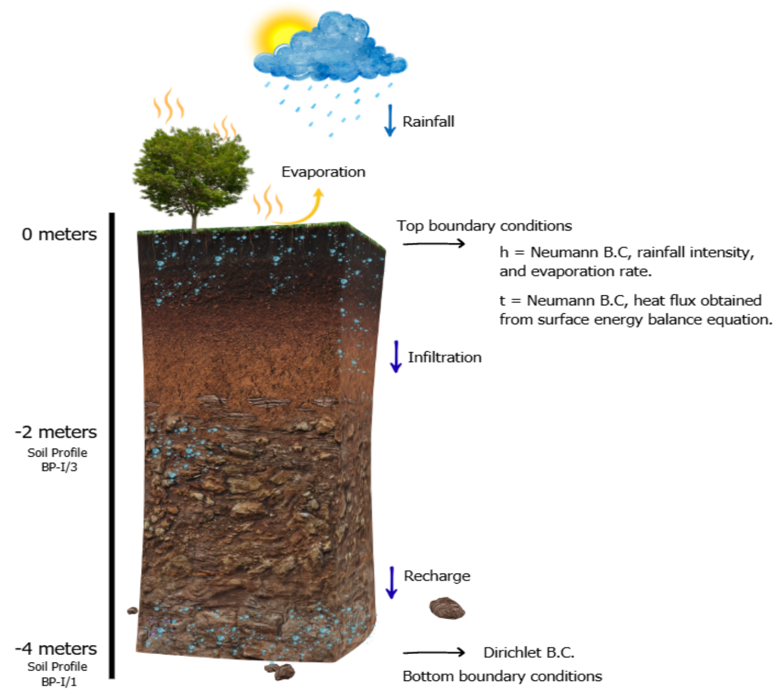

Figure 4: Schematic representation of the modelled soil column (0 to 4 m) and the main vertical fluxes (rainfall, evaporation, infiltration, and recharge). The top boundary is defined by Neumann boundary conditions for pressure head (as a function of rainfall intensity and evaporation rate) and for temperature **T** (heat flux derived from the surface energy balance), while the bottom boundary is prescribed as a Dirichlet condition. Own elaboration.

3.1.2. Boundary Conditions

Bottom boundary conditions. To ensure numerical stability, the model imposes Dirichlet boundary conditions for both pressure head (h) and temperature (T) at the bottom boundary. Although a free-drainage condition is commonly applied at the base of soil profiles, using it in this case would lead to a Neumann-only boundary formulation, which is often more susceptible to numerical instabilities. The lower boundary is located sufficiently deep relative to the land surface and the groundwater-recharge reference depth; therefore, prescribing constant boundary values (set to the mean h and T)

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has a negligible influence on the simulated solution at the reference point. The prescribed Dirichlet values are $h = 0$ and $T = 7^{\circ}$ C, which means groundwater table and average annual temperature for the study region.

Top boundary conditions. The top boundary conditions are based on Saito et al. (2006); Sakai et al. (2011) model formulation. For the water flow equation, the top boundary condition was given by time-dependent rainfall and actual evaporation rate; for the heat equation, it was time-dependent soil heat flux obtained from the surface energy balance equation. Both conditions were Neumann-type conditions.

Groundwater recharge reference point. The groundwater recharge reference point was defined at the mid-depth of the computational domain for both profiles. This location was selected to ensure sufficient separation from the lower Dirichlet boundary and from the upper boundary representing atmospheric forcing. At the same time, it is deep enough for all relevant vadose-zone processes—such as root water uptake and vadose-zone transformations—to fully develop above this point.

3.1.3. Initial Conditions

Since the initial conditions of the soil groundwater system are often impossible to achieve and since we presume that, for our long-term simulation, the effect of the initial condition is negligible, we considered here a constant and average distribution of soil temperature and water content.

Soil layers distribution, and material properties. The van Genuchten parameters describe the soil's water retention and hydraulic conductivity, which are essential for modelling water movement through the soil. These values are part of the van Genuchten model, widely used to simulate the relationship between soil moisture, pressure head, and hydraulic conductivity, particularly in unsaturated soils.

For Amalie Lany, the model was constructed with seven layers, each with seven van Genuchten parameters, for the soil profile BP-I/1, and with five layers, each with five van Genuchten parameters, for the soil profile BP-I/3. The data used on van Genuchten came from 2 different sources. The first source is data in situ, samples taken in the Amalia Lány watershed. This

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data was taken directly on two borehole profiles, considering only the first 20cm, and then the saturated volume, water content (θs) was estimated in a laboratory. For the lower soil horizons, this research handled soil type specifications (see Figure 3.

The hydraulic properties of the lower soil horizons were defined using parameter values reported by some authors as Carsel and Parrish (1988), Hilberts et al. (2005), Ghanbarian-Alavijeh et al. (2010) as a reference. The vegetation cover at the study site was taken from the publication of Chytrỳ (2012) and the uptake of root water was described according to the stress response function Feddes et al. (1978). The corresponding root water uptake parameters were adopted as reference from Schreel (2019), Rabbel et al. (2018). All soil hydraulic and vegetation-related parameters used in the simulations are listed in Tables 1 and 2.

Layer	Vertical Depth [m]	α [cm^{-1}]	n	m	θ_r	θ_s	K_s [cm s^{-1}]
1	0.00–0.04	0.543	3.047	1.330	0.090	0.627	1.61×10^{-6}
2	0.04–0.10	0.717	3.160	1.317	0.220	0.460	1.52×10^{-6}
3	0.10–0.20	0.503	2.900	1.390	0.000	0.437	1.42×10^{-6}
4	0.20–1.00	1.860	1.450	0.310	0.015	0.480	1.00×10^{-6}
5	1.00–2.00	0.990	1.430	0.300	0.020	0.500	7.86×10^{-6}
6	2.00–3.00	1.860	1.450	0.310	0.015	0.480	1.50×10^{-5}
7	3.00–4.00	0.430	1.360	0.260	0.030	0.520	1.50×10^{-5}

Table 1: Van Genuchten soil hydraulic parameters for soil profile BP-I/1

Layer	Vertical Depth [m]	α [cm^{-1}]	n	m	θ_r	θ_s	K_s [cm s^{-1}]
1	0.00–0.04	0.553	3.473	1.287	0.163	0.703	1.56×10^{-6}
2	0.04–0.10	0.583	3.253	1.307	0.210	0.453	1.53×10^{-6}
3	0.10–0.20	0.403	2.823	1.360	0.000	0.407	1.51×10^{-6}
4	0.20–1.00	0.586	3.254	0.692	0.210	0.455	7.86×10^{-5}
5	1.00–2.00	0.586	3.254	0.692	0.210	0.455	7.86×10^{-5}

Table 2: Van Genuchten soil hydraulic parameters for soil profile BP-I/3

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3.2. Simulation Period

3.2.1. Historical Simulation

The climatic data (from 1990 to 2020) were obtained by the Czech Hydrometeorological Institute (CHMI) from the meteorological stations closest to the study area. The Lany meteorological station was selected to analyse the climatic variability in the Amalia Lány area, which holds the longest climate records available for this area. The dataset from 1990 to 2020 included precipitation, maximum and minimum air temperature, relative humidity, wind speed, and cloud cover. As solar radiation measurements were unavailable, hourly clear-sky global horizontal irradiance (GHI) was estimated in RStudio R Core Team (2024). Solar altitude was calculated using the `getSunlightPosition()` function from the `suncalc` package (Thieurmel and Elmarhraoui, 2026), and GHI was subsequently estimated using the Haurwitz clear-sky model (Haurwitz, 1945; Reno et al., 2012).

This synthetic data was disaggregated from daily to hourly scale using data from The Fifth Generation ECMWF Reanalysis (ERA5), which operates on an hourly time scale. ERA5 Hersbach et al. (2018) is a comprehensive reanalysis dataset, available since 1959, that assimilates a wide range of atmospheric and surface-level observations. (`https://cds.climate.copernicus.eu/`).

Reanalysis Dataset Disaggregation. ***Precipitation an temperature disaggregation***

Precipitation and temperature disaggregation was used to adjust ERA5 hourly data to locally observed conditions. For precipitation, observed daily totals were used to correct potential biases in ERA5 estimates by proportionally redistributing hourly precipitation according to the model's temporal pattern. For temperature, ERA5 hourly values were adjusted using locally recorded daily maximum and minimum temperatures, ensuring that diurnal variability and temperature extremes more realistically represented the conditions observed at the station. This procedure provided more consistent and representative hourly series for subsequent hydrological and climate analyses.

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3.2.2. Climate Model Projections

The evaluation and assessment of climate models have been largely guided by the Coupled Model Intercomparison Project (CMIP), which has dominated the field of climate change attribution and future projections for the past two decades Kelley et al. (2020). This international project involves extensive collaboration between climate modelling groups worldwide. The last phase, CMIP6, began accepting data in 2018 in preparation for the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6) Eyring et al. (2016). These models provide critical information to understand regional climate impacts and develop strategies for climate adaptation. The climate models used in this research are described below.

Modelling Centre	Model	Country	Resolution	Ensemble	Scenarios
Australian Community Climate and Earth System Simulator	ACCESS-CM2	Australia	$\sim 1.25° \times 1.875°$	r1i1p1f1	SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5
The Canadian Earth System Model	CanESM5	Canada	$\sim 2.81° \times 2.81°$	r1i1p1f1	
Centre National de Recherches Météorologiques – Earth System Model	CNRM-ESM2-1	France	$\sim 1.40° \times 1.40°$	r1i1p1f2	
Geophysical Fluid Dynamics Laboratory Earth System Model	GFDL-ESM4	USA	$1.0° \times 1.0°$	r1i1p1f1	
Institute for Numerical Mathematics	INM-CM5	Russia	$1.5° \times 2.0°$	r1i1p1f1	
Institut Pierre-Simon Laplace	IPSL-CM6A-LR	France	$\sim 1.3° \times 2.5°$	r1i1p1f1	
Max Planck Institute Earth System Model	MPI-LR	Germany	$\sim 1.875° \times 1.875°$	r1i1p1f1	
The Meteorological Research Institute Earth System Model Version 2.0	MRI-ESM2-0	Japan	$1.125° \times 1.125°$	r1i1p1f1	

Table 3: Overview of the CMIP6 Earth System Models used in long term groundwater recharge.

Shared Socio-economic Pathways (SSPs). Shared Socioeconomic Pathways (SSPs) are forward-looking development pathways used to explore possible futures of socioeconomic development throughout the 21st century. The SSPs consist of five scenarios, each characterised by different socio-economic conditions, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development Riahi et al. (2017). These scenarios provide an essential framework for assessing the potential impacts of different socio-economic trends on climate change. The Radiative Concentration Pathways (RCPs) provide a set of greenhouse gas concentration trajectories that define the level of radiative forcing by the end of the century. The RCPs are used with SSPs to determine the level of climate

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change mitigation required to meet specific targets. In this study, four SSP-based scenarios are used, categorized along two axes: challenges to mitigation and adaptation.

1. SSP1 (Sustainability): Low challenges for mitigation and adaptation Riahi et al. (2017).
2. SSP2 (Middle of the Road): Medium challenges to mitigation and adaptation Riahi et al. (2017); Van Vuuren et al. (2017).
3. SSP3 (Regional Rivalry): High challenges to mitigation and adaptation. Riahi et al. (2017)
4. SSP5 (Fossil-fueled Development): High challenges to mitigation, low challenges to adaptation Riahi et al. (2017); Kriegler et al. (2017)

Joint Variable Bias Correction and downscaling (JVBCD). The methodology employed in this research is called Joint Variable Bias Correction and Downscaling (JVBCD), whose mathematical foundation of JVBCD lies in its ability to address joint probability distributions and the preservation of inter-variable dependencies. This method is designed to correct statistical biases in the projections of the General Circulation Model (GCM) while maintaining significant spatial and temporal relationships between climate variables, such as the correlation between temperature and precipitation Zhang and Georgakakos (2012), El Sharif and Georgakakos (2023b), El Sharif and Georgakakos (2023a).

3.3. Definition of indicators for hypotheses evaluation

To evaluate the working hypothesis that, under ongoing climate change, evaporation in the Amalia Lány watershed will increase while groundwater recharge will decline due to higher atmospheric demand and altered precipitation patterns (see Section 1), a set of quantitative indicators was defined for both groundwater recharge and evapotranspiration. These indicators were derived from the simulation of Richards and the heat flow equation using the setup from 3.1 Saito et al. (2006) and Sakai et al. (2011), for the two soil profiles (BP-I/1 and BP-I/3) and were computed consistently for the historical baseline and all future climate periods. Groundwater recharge was represented by the simulated deep percolation at the lower boundary of the soil column, i.e. the downward water flux across the groundwater table prescribed by the Dirichlet condition (Section 3). Actual evaporation was defined as the sum of simulated soil evaporation at the upper boundary of

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the soil profile.

In order to reduce the influence of interannual variability and to highlight long-term behaviour, annual recharge and evapotranspiration series were further averaged over decadal periods for the historical baseline (1990–2019) and for each future scenario considered: SSPs1-2.6, SSPs2-4.5, SSPs3-7.0, and SSPs4-8.5. For each climate model and scenario combination, loess trends in decadal were estimated. To quantify the magnitude of climate-driven changes, anomalies of recharge and evaporation were computed for each period as differences relative to the historical baseline means.

Taken together, these indicators allow a direct test of the hypothesis that (i) actual and future evaporation increases in response to enhanced atmospheric demand, and (ii) groundwater recharge declines under the combined effects of warming and modified precipitation regimes in the Amalia Lány watershed. The sign, magnitude and significance of the simulated trends, as well as the relative changes between periods, are therefore used as the primary criteria for accepting or rejecting the working hypothesis.

Model simulations were performed using the disaggregated hourly meteorological forcing derived from ERA5 and local observations. Each climate scenario was computed independently using a single CPU core. Considering two soil profiles and 32 climate combinations, corresponding to eight climate models and four emission scenarios, a total of 64 CPU cores were used. The simulations were run on a workstation equipped with an Intel(R) Core(TM) i9-14900K CPU architecture. The total simulation runtime was 25.6 days for profile BP-I-1 and 12.1 days for profile BP-I-3.

The number of simulation time levels corresponded to the number of records available in the observation files, with each record representing one hourly input step. In total, 21,039,779 time levels were simulated, requiring 21,287,360 calls to the linear equation solver, with an average of 1.011767 solver iterations per time level. For each iteration, the BP-I-1 profile included 322 unknowns, corresponding to 171 nodes with two unknowns per node: temperature, T, and pressure head, h. For the BP-I-3 profile, the numerical problem included 152 unknowns, corresponding to 71 nodes.

Model outputs were subsequently aggregated according to the variable an-

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alyzed. Flux-related variables, such as precipitation, infiltration, and groundwater recharge, were accumulated over daily periods, whereas state variables, such as temperature, soil moisture, and pressure head, were summarized using mean values. This aggregation allowed the hourly simulations to be interpreted at hydrologically meaningful temporal scales and compared with observed and scenario-based climate indicators.

4. Results and Discussion

4.1. Groundwater Recharge 1990-2020

Groundwater recharge during 1990–2020 exhibits clear interannual variability driven primarily by precipitation dynamics and moderated by atmospheric demand. In general, recharge increases during wetter years and decreases during extended dry spells, reflecting the dependence of infiltration-driven recharge on rainfall intensity, event sequencing, and antecedent soil moisture. Results for the section 4.1 are presented in 2 soils profiles: Soil Profile BP-I/1 (section 4.1.1) and Soil Profile BP-I/3 (section 4.1.2).

4.1.1. Soil Profile BP-I/1

Infiltration analysis for the BP-I/1 was conducted at the lower point. Figure 5 illustrates the correlation between precipitation and aquifer recharge at -4 meters. The correlation between precipitation and aquifer recharge from 1990 to 1999 was relatively stable, with recharge rates generally fluctuating between 1 mm/day and 3 mm/day in response to varying precipitation levels. There are instances of minor recharge spikes following significant precipitation events, indicating a steady but moderate recharge process. The period from 2000 to 2010 marks a phase of increased variability in both precipitation and aquifer recharge. Notable negative recharge events were observed around 2000/2001, corresponding to periods of high precipitation followed by rapid declines in recharge. This suggests potential saturation or runoff effects, in which excess rainfall could not be effectively absorbed by the aquifer, leading to temporary drops in recharge rates.

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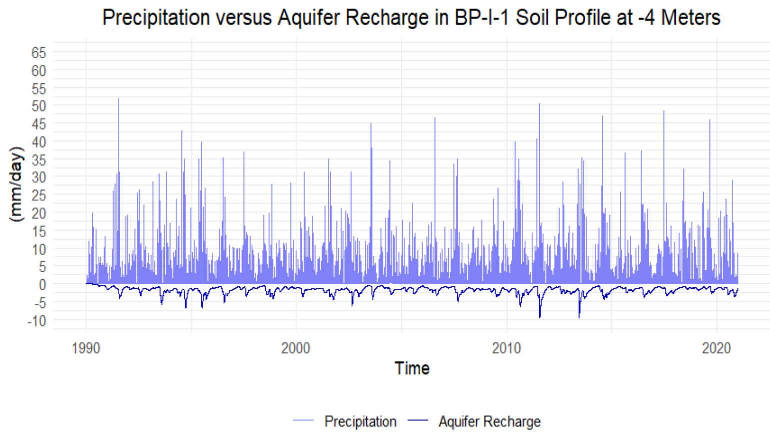

Figure 5: Precipitation versus aquifer recharge at -4 meters soil profile BP-I/1

In the last decade of Figure 5, the recharge behaviour gradually returns to a more stable pattern, despite some negative recharge spikes still evident around the early 2010s. The frequency and intensity of precipitation events influence the overall recharge rates. Still, there appears to be a slight negative trend in stabilisation towards the end of this period, indicating a potential decline in aquifer recharge.

Regarding the data variability, in autumn, recharge shows an initial positive trend, a decline around 1997–2002/03, recovery through 2012/13, and a renewed decrease toward 2020. Spring increases by ≈0.5 mm during 1990–1998, followed by a sustained negative trend through 2020 (a cumulative decline of about 0.2–0.3 mm), consistent with declining precipitation, higher maximum temperatures, increased evapotranspiration, and altered soil-moisture dynamics. Summer showed a modest rise in 1990–1995 (∼+0.3 mm) is followed by a decline in 1998–2002/03 (≈–0.3 mm), a rebound peaking near 2010 (≈+0.5 mm), and then a sharp drop by 2020 (≈–0.7 to –0.8 mm). Winter exhibits subtler variability, with a small rise in the early 1990s (≈+0.3 mm), a mild dip around 2000–2005, recovery during 2005–2015, and a gradual shift toward negative trends after 2015.

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4.1.2. Soil Profile BP-I/3

Figure 6 illustrates that while precipitation events are frequent and exhibit significant peaks, the corresponding aquifer recharge shows less variability and lower magnitude changes in response to these events. This pattern suggests an effect of soil and geological properties on water infiltration, where only a fraction of the precipitation effectively contributes to groundwater recharge.

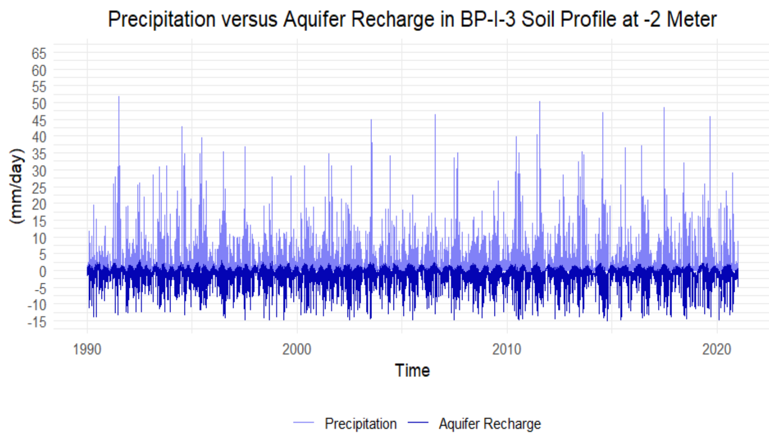

Figure 6: Precipitation versus aquifer recharge at -2m, soil profile BP-I/3

Notable peaks in precipitation, particularly those exceeding 20 mm/day, do not always directly correspond to significant increases in recharge rates, indicating that other factors such as soil saturation, antecedent moisture conditions, and evapotranspiration could play a crucial role in limiting the amount of water that reaches the aquifer. The relatively stable but lower magnitude of recharge compared to precipitation highlights the delayed and diffuse nature of groundwater replenishment at this depth, which could be due to slow percolation rates and the buffering capacity of the soil layers.

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4.2. Long-Term Assessment of Groundwater Recharge in the Amalie Lany Aquifer

4.2.1. Soil Profile BP-I/1

The figure 7 illustrates the long-term anomalies of groundwater recharge in the Amalie Lany Aquifer for the BP-I/1 soil profile under four climate scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) and five soil depths (-0.10 m, -0.50 m, -1.00 m, -2.00 m, and -3.00 m). Overall, the results show that recharge anomalies are generally small during the early decades but become increasingly negative under the more severe emissions pathways, particularly after mid-century. This indicates a progressive reduction in groundwater recharge relative to the reference period, with the strongest declines occurring under higher greenhouse gas forcing.

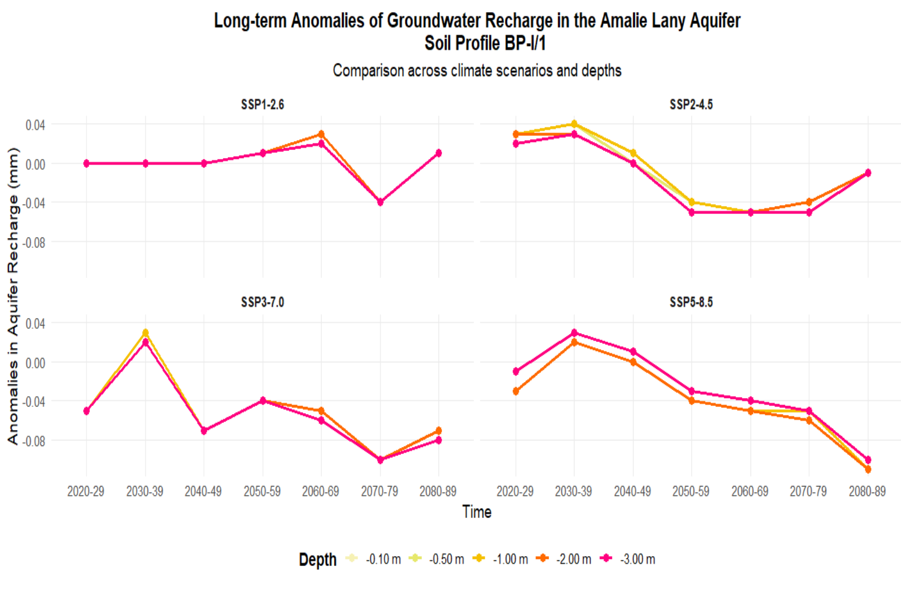

Figure 7: Long-Term Anomalies of Groundwater Recharge in the Amalie Lany Aquifer, Soil Profile BP-I/1.

- ***SSP1-2.6***: Under SSP1-2.6, recharge anomalies remain modest throughout the century: near-zero at all depths in 2020–2049, a mid-century increase peaking around $+0.03$ mm that is most pronounced in the shallow layers (-0.10 and -0.50 m), and a late-century decline, especially

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at depth (−2.00 and −3.00 m), reaching about −0.04 mm. The shallow layers show more consistent, slightly positive anomalies, whereas the deeper layers are more variable and exhibit the strongest late-century reductions. Overall, the anomaly range is narrow (≈ −0.04 to +0.03 mm), indicating only minor changes in groundwater recharge.

- ***SSP2-4.5***: Under SSP2-4.5, recharge anomalies are initially slightly positive across all depths, peaking at about +0.03–0.04 mm in 2030–2039 (most pronounced in the shallow layers), before declining to near zero by 2040–2049. From 2050 onward, negative anomalies dominate, reaching around −0.05 mm in the deeper layers (−2.00 to −3.00 m) during the 2060s–2070s, suggesting reduced recharge under changing climatic conditions. By 2080–2089, anomalies stabilize near −0.01 mm, with deeper layers remaining more adversely affected than shallow ones.

- ***SSP3-7.0***: Under high emissions, recharge anomalies shift from slightly positive in 2020–2039 (+0.02 to +0.04 mm, strongest in the shallow layers) to negative in 2040–2069 (≈ −0.05 to −0.07 mm, particularly at depth), and remain predominantly negative by 2070–2089. By late century, the deepest layer (-3.00 m) approaches −0.08 mm, while the shallow layers are around −0.07 mm, indicating a sustained, depth-amplified decline in groundwater recharge.

- ***SSP5-8.5***: Under an extreme-emissions scenario, recharge anomalies are slightly positive in 2020–2039 (up to ∼+0.03 mm at −0.10 m), turn negative by 2040–2049, and worsen after 2050, particularly at depth (−2.00 to −3.00 m; ∼ −0.06 mm). By 2080–2089, declines are substantial across all depths, with the deepest layer (−3.00 m) exhibiting the largest deficits (∼ −0.10 to −0.11 mm). Overall, deeper aquifer zones are most affected, underscoring heightened vulnerability and the need for proactive groundwater management.

4.2.2. Soil Profile BP-I/3

The figure 8 presents the long-term anomalies of groundwater recharge in the Amalie Lany Aquifer for the BP-1/3 soil profile under four climate scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) and three depths within the soil profile (-0.10 m, -0.50 m, and -1.00 m). Overall, the results indicate that groundwater recharge anomalies are predominantly negative

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across most decades, suggesting a long-term reduction in recharge relative to the reference period.

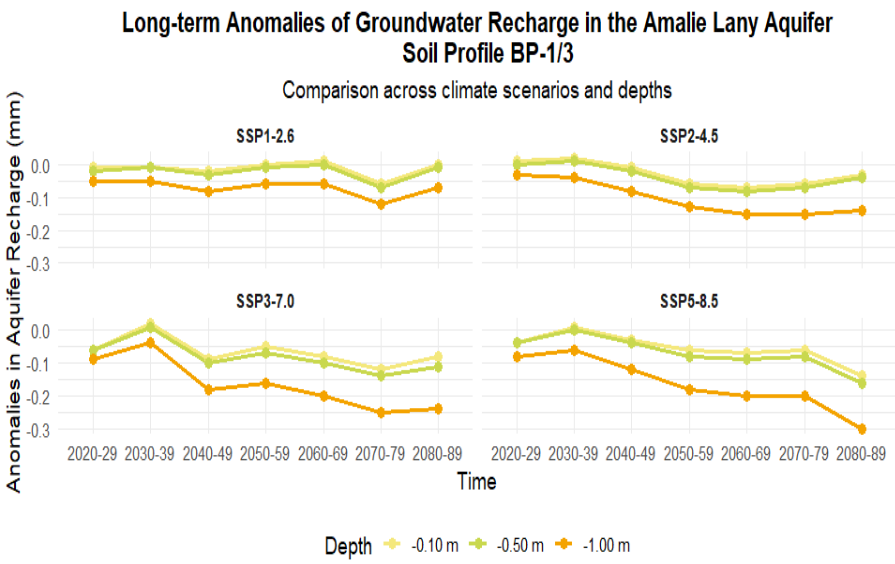

Figure 8: Long-Term Anomalies of Groundwater Recharge in the Amalie Lany Aquifer, Soil Profile BP-I/3.

- ***Shared Socioeconomic Pathways (SSP1-2.6)***: Groundwater recharge anomalies grow as groundwater levels drop, revealing higher system sensitivity with depth. Shallow levels (-0.10 m) stay near zero (≈ 0 to -0.01 mm), indicating resilience; mid-depth (-0.50 m) shows moderate, steadily worsening deficits (≈ -0.01 mm in 2020–2029 to ≈ -0.07 mm by 2080–2089); and deeper levels (-1.00 m) experience the largest declines (≈ -0.05 mm early, reaching ≈ -0.12 mm by century's end). Anomalies intensify after $\sim$2040, making 2040–2089 a critical window, especially at -1.00 m, underscoring the need for timely, adaptive groundwater-management measures to mitigate worsening recharge deficits.

- ***Shared Socioeconomic Pathways (SSP2-4.5)***: Recharge declines over time, with relatively favourable levels in 1990–2009 and widening

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scenario differences from mid-century onward. Shallow groundwater (-0.10 m) is the most stable, averaging about 0.70–0.80 mm early in the record and settling near ∼0.60 mm later, whereas mid-depth (-0.50 m) decreases from ∼0.70 mm to ∼0.50–0.55 mm by century's end. The deepest level (-1.00 m) exhibits the steepest losses, falling from ∼0.65 mm to below 0.50 mm, highlighting the greater sensitivity of deeper zones to combined climatic and hydrological pressures. Shallow water tables (-0.10 meters) show minimal anomalies throughout the century, with values ranging from 0.00 to -0.03 mm, indicating low variability to climatic stress. Moderate water tables (-0.50 meters) exhibit slightly larger anomalies, reaching a peak at -0.07 mm between 2060 and 2069, suggesting a progressive sensitivity to emissions and hydrological changes. However, deeper point observation (-1.00 meters) experienced the most pronounced declines, with anomalies worsening significantly after 2040 and reaching critical values of -0.15 mm in 2070–2079 and -0.14 mm in 2080–2089.

- ***Shared Socioeconomic Pathways (SSP3-7.0)***: For the SSP3-7.0, the shallow groundwater (-0.10 m) maintains the highest and most stable recharge over time, showing the lowest impact from climate and hydrological changes. Intermediate depth (-0.50 m) experiences a moderate but progressive decline. The deepest level (-1.00 m) is the most vulnerable, with the recharge dropping the fastest and the most, especially after 2040, and stabilizing at values below 0.40 mm by 2080–2089.The problems in recharge are small for shallow water tables (-0.10 m). Moderate depths (-0.50 m) show a gradual worsening, reaching around -0.14 mm by 2080–2089. The deepest level (-1.00 m) experiences the largest anomalies, dropping to about -0.25 mm around 2070–2079 and remaining strongly negative afterwards. The period 2040–2089 is a turning point: anomalies increase dramatically in all cases, but especially for -1.00 m, revealing that deeper aquifers are much more vulnerable to combined climate change and groundwater stress.

- ***Shared Socioeconomic Pathways (SSP5-8.5)***: Shallow water tables (-0.10 m) remain largely resilient, with recharge anomalies remaining very small throughout the century. Moderate depths (-0.50 m) show a steady but limited decline, reaching about -0.14 mm by 2080–2089. In contrast, deep water tables (-1.00 m) experience the strongest im-

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pact: anomalies intensify after 2040, reaching around -0.25 mm before slightly stabilising, revealing high vulnerability to climate and groundwater stress. The period 2040–2089 is a critical turning point, when anomalies grow sharply, and the contrast between shallow, moderate, and deep water tables becomes much more pronounced as greenhouse gas emissions increase.

4.3. Long-term evaporation

Figure 9 displays long-term anomalies in evaporation for the topsoil layer in the Amalie Lany region under the greenhouse gas emissions scenarios. The anomalies are presented as deviations (mm/day) across different decades, reflecting shifts in evaporation patterns over time. The figure illustrates the long-term evolution of evaporation anomalies in the Amalie Lany topsoil layer under four Shared Socioeconomic Pathway (SSP) climate scenarios from the 2020s to the 2080s. Overall, all scenarios show positive anomalies throughout the study period, indicating a persistent increase in evaporation relative to the reference baseline. However, the magnitude and temporal progression of these anomalies differ substantially among scenarios, with stronger greenhouse gas emission pathways generally producing larger increases in evaporation over time.

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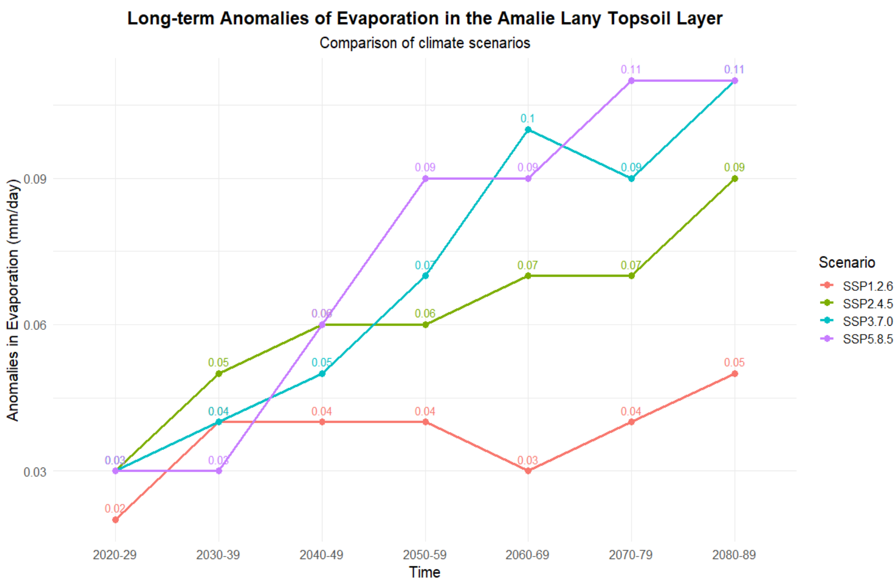

Figure 9: Long-term Anomalies of Evaporation in the Amalie Lany Topsoil Layer

- ***Low Greenhouse Gas Emissions (SSP1-2.6)***: the data for this scenario reveal a gradual increase in evaporation anomalies from 2020 to 2089, highlighting a consistent upward trend over time. Starting at 0.02 mm/day during 2020-2029, the anomalies increase steadily, reaching 0.05 mm/day in 2080-2089. This progression suggests a warming climate, even under a low-GHG scenario, with rising temperatures and shifting atmospheric conditions likely driving higher evaporation rates. Despite the overall increase, the anomalies exhibit minor fluctuations between decades. From 2030–2039 to 2050–2059, the anomalies remain stable at 0.04 mm/day. However, during 2060–2069, a slight decline was observed to 0.03 mm/ day before it rose again to 0.05 mm/day in the 1980s.

- ***Intermediate Greenhouse Gas Emissions (SSP2-4.5)***: The Anomalies start at 0.03 mm/day during the 2020-2029 period and increase incrementally over time, reaching 0.09 mm/day in the 2080-2089 period. This upward trend reflects the influence of moderate greenhouse gas emissions on atmospheric and soil dynamics, leading to enhanced

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evaporation rates. From 2030 to 2049, the anomalies climb from 0.05 mm/day to 0.06 mm/day, while the 2050s and 2060s exhibit similar rates. By the 2020s and 2080s, the anomalies escalated further to 0.07 mm/day, eventually reaching 0.09 mm/day.

- ***High Greenhouse Gas Emissions (SSP3-7.0)***: Evaporation shows a consistent incremental increase across the decades, with several notable milestones. During the 2020–2029 period, it rises gradually from 0.66 mm/day to 0.70 mm/day, marking the early phase of warming effects under a high-emissions pathway. A sharper increase is observed between 2030 and 2059, when evaporation rates climb from 0.72 mm/day to 0.75 mm/day, likely reflecting the influence of stronger mid-century temperature increases. This upward trend continues during 2060–2089, with evaporation reaching 0.77 mm/day and finally 0.78 mm/day in the last decade, highlighting the cumulative and compounding effects of sustained greenhouse gas emissions.

- ***Very High Greenhouse Gas Emissions (SSP5-8.5)***: Long-term anomalies of evaporation in the Amalie Lany under the very high greenhouse gas emission highlight a progressive increase in evaporation anomalies over the studied period. Beginning at 0.03 mm/day in the 2020–2029 decade, the anomalies double to 0.06 mm/day by 2040–2049 and continue to increase steadily to 0.11 mm/day by the 2080–2089 period. Distinct milestones mark the growth in anomalies. A notable increase occurs between 2040–2059, with anomalies rising sharply from 0.06 mm/day to 0.09 mm/day, and this level is maintained through 2060–2069. By the final two decades, 2070–2089, anomalies peak at 0.11 mm/day, indicating a consistent trajectory toward greater evaporation under extreme emissions scenarios.

4.4. Effects of Precipitation and Temperature in Lany Groundwater Recharge

The results from the Lány site reveal a central hydroclimatic message: groundwater recharge is not controlled by precipitation alone, but by the interaction between rainfall, temperature, evaporation, soil hydraulic properties, and the timing and intensity of meteorological events. This finding is consistent with previous studies showing that recharge dynamics in Central European hydrogeological systems are highly sensitive to rainfall variability (Haidu and Nistor (2020); Nistor (2019)). Because precipitation governs

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the volume of water available for infiltration, fluctuations in its amount and timing directly affect subsurface recharge processes and, ultimately, the long-term sustainability of groundwater resources (Grinevskiy et al. (2021), and Szűcs et al. (2020)). This confirms that groundwater recharge in Central Bohemia is highly climate-sensitive and that even modest changes in hydroclimatic balance can alter subsurface replenishment.

When observing the historical basis in the study area, the dry years of 2015, 2018, and 2019 clearly illustrate this sensitivity. During these years, reduced precipitation produced marked declines in recharge at Amalie Lány, supporting the conclusion that recharge in this hydrogeological setting is highly vulnerable to rainfall deficits. The pronounced rainfall deficit in 2015 caused soil desiccation and affected vegetation health in Central Europe, as observed in the Czech Republic, Poland, and Slovakia Orth et al. (2016). However, the recharge signal is not simply a linear response to annual precipitation totals. Rather, the results suggest that persistent precipitation deficits, when combined with warmer conditions, amplify recharge decline by reducing soil moisture availability and increasing atmospheric water demand, thereby weakening the effective transfer of water into deeper subsurface layers. This is particularly important in the lower layer, where the correlation between rainfall deficits and recharge reduction appears stronger, indicating greater sensitivity to long-term hydroclimatic stress.

These findings are consistent with broader evidence from the Czech Republic and Central Europe, where severe droughts have repeatedly affected water resources during the last decades (Potopová et al. (2018); Trnka et al. (2016); Brazdil et al. (2015); Hlavinka et al. (2015); Dubrovsky et al. (2009)). In Lány, the influence of drought is especially apparent during spring, when reduced rainfall, positive temperature anomalies, lower cloud cover, and enhanced potential evapotranspiration collectively suppress recharge. The prolonged dry phase between 2014 and 2019, therefore, should not be interpreted as a sequence of isolated anomalies, but rather as part of a larger regional pattern of hydroclimatic deterioration affecting groundwater systems. In this context, Lány acts as a representative local-scale observatory of broader environmental change in Central Europe.

The period between 2014 and 2019, characterised by prolonged dry conditions, resulted in a significant reduction in groundwater levels, as corrobo-

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rated by data from the Czech Hydrometeorological Institute (CHMI) monitoring network Kašpárek et al. (2022). These droughts were exacerbated by positive temperature anomalies, reduced cloud cover, and increased potential evapotranspiration (PET), conditions that severely limited soil moisture availability, further stressing groundwater resources Potop et al. (2014). A key contribution of this study is that it demonstrates a critical paradox of climate change impacts on groundwater: stable or near-stable mean precipitation does not necessarily imply stable groundwater recharge.

4.4.1. Longterm Groundwater Recharge

Projected warming in the Lány area under all SSP pathways represents a major constraint on future groundwater recharge. In particular, the high-emission scenarios SSP3-7.0 and SSP5-8.5 indicate a progressively less favourable recharge regime, as rising temperatures are expected to intensify evaporative losses and reduce the fraction of precipitation that effectively infiltrates into the aquifer. This is not a marginal adjustment in the water balance, but a structural shift in recharge efficiency under climate forcing. In this regard, Kašpárek (2007) reported an increase in evaporation of approximately 5 mm in Central Europe, a trend that is fully consistent with the projected warming for Amalie Lány. If this thermal trajectory persists through 2089, the hydrological consequence is clear: even in the absence of large declines in annual precipitation, aquifer replenishment may become increasingly constrained by climate-driven atmospheric demand.

A key finding of this study is the identification of a critical hydroclimatic paradox: stable or near-stable mean precipitation does not necessarily translate into stable groundwater recharge. During the short-term period (2020–2034), projected precipitation remains nearly constant, averaging 1.58 mm/year, while temperature variability across SSP scenarios is relatively limited, ranging from 9.35°C to 9.49°C. Under these apparently stable climatic conditions, simulated recharge remains broadly similar across most scenarios, with SSP1-2.6, SSP2-4.5, and SSP5-8.5 yielding values close to 1.20 mm/day and SSP3-7.0 showing a slightly lower recharge rate of 1.16 mm/day. However, this apparent short-term stability should not be interpreted as evidence of hydrological resilience. Rather, it may reflect a transient balance in which the effects of warming are still modest enough to avoid a pronounced disruption of recharge processes, even though the system may already be moving

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toward a less efficient rainfall–recharge relationship.

In the mid-term period (2035–2059), all SSP scenarios project continued warming, with mean annual temperatures increasing from 9.73°C under SSP1-2.6 to 10.27°C under SSP5-8.5. This sustained thermal rise is likely to impose increasing constraints on groundwater recharge, even though mean annual precipitation remains broadly stable at around 1.60 mm/day. Under these conditions, higher temperatures are expected to enhance evaporation and evapotranspiration, thereby reducing the fraction of precipitation that effectively infiltrates into the aquifer. The progressive decline in simulated recharge across most scenarios reflects this emerging imbalance, with recharge decreasing to 1.18 mm/day under SSP1-2.6, 1.16 mm/day under SSP2-4.5, and 1.14 mm/day under SSP3-7.0. The hydrological significance of this result is substantial: climate warming can reduce net recharge even in the absence of major declines in annual precipitation. This decoupling between rainfall totals and recharge is one of the most important implications of the study, as it indicates that groundwater vulnerability may intensify under climate change even where precipitation projections appear relatively neutral. In this sense, the mid-century projections suggest that groundwater systems in Lány may become increasingly vulnerable not because of precipitation variability, but because warming progressively makes precipitation less effective as a recharge source.

Interestingly, the SSP5-8.5 scenario yields a slightly higher recharge rate (1.19 mm/day) despite being associated with the highest projected mean temperature (10.27°C). Rather than indicating improved groundwater conditions, this apparent anomaly likely reflects the increasing contribution of extreme precipitation events under high-emission forcing. Although such events can temporarily enhance water input and generate short-term recharge pulses, they do not necessarily support sustained aquifer replenishment. In fact, intense rainfall is often hydrologically inefficient, as a substantial fraction of the water may be rapidly lost through surface runoff and flash flooding before effective infiltration can occur. Consequently, the modest recharge increase projected under SSP5-8.5 should be interpreted with caution: it may represent greater hydrological variability rather than greater groundwater resilience. This distinction is critical, because the combination of rising temperatures, intensified evaporative demand, and more erratic precipitation regimes may ultimately compromise the long-term sustainability of ground-

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water resources, even where modeled recharge appears superficially stable or slightly enhanced Ionita et al. (2020); Lobanova et al. (2018); Roudier et al. (2016); Stagl et al. (2014).

In the long-term period (2060–2089), recharge in Lány appears numerically stable but becomes increasingly fragile in physical terms. Although mean annual precipitation remains close to 1.60 mm/year, all SSP scenarios project substantial warming (Lu et al. (2026), Kumar et al. (2025), Zarei et al. (2025)), with mean annual temperature rising from 9.88°C under SSP1-2.6 to 11.22°C under SSP5-8.5. Recharge values remain within a narrow range (1.16–1.19 mm/day) under SSP1-2.6, SSP2-4.5, and SSP3-7.0, but this should not be interpreted as long-term hydrogeological stability. Rather, it suggests that warming progressively alters recharge processes without necessarily producing an immediate decline in modeled totals. The slightly higher recharge projected under SSP5-8.5 (1.22 mm/day), despite the strongest warming, likely reflects the growing influence of extreme rainfall events that may increase short-term water input without improving sustained aquifer replenishment. Thus, the long-term response points to a more unstable and potentially less reliable recharge regime, even where average recharge appears superficially unchanged.

Although seemingly positive, the projected increase in aquifer recharge under the SSP5-8.5 scenario must be critically assessed in light of geological and soil parameters that significantly affect water infiltration and recharge. In Lány, as in many regions, soil permeability and geological formation play crucial roles in determining the efficiency and rate of groundwater recharge Li et al. (2020); Nicolas et al. (2019); Singhal and Gupta (2010). The slow permeability observed in the soil profiles studied suggests that, despite an increase in precipitation and the occurrence of extreme rainfall events, the actual infiltration of water into the aquifers could be limited. This reduced infiltration can be attributed to the difficulty with which water is encountered in percolating through the soil, especially during intense precipitation events, where water may not have sufficient time to infiltrate before being lost as runoff.

Under high-emission scenarios such as SSP5-8.5, extreme precipitation events may increase modeled recharge, but this response should be interpreted cautiously. Heavy rainfall concentrated over short periods is often

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hydrologically inefficient for long-term aquifer replenishment, because a large fraction of the incoming water may be lost through rapid surface runoff and flash flooding rather than effective infiltration. As a result, these events can amplify recharge variability and generate short-term recharge pulses without necessarily improving sustained groundwater storage. This interpretation is consistent with previous studies showing that intensified precipitation under warming scenarios often increases hydrological extremes rather than enhancing reliable recharge processes Nazarenko et al. (2025); Khoirunisa (2022); Mukherji (2023).

A further concern is that recharge effectiveness under such conditions is strongly constrained by subsurface properties. Even where total precipitation increases, the actual contribution to groundwater storage may remain limited by soil permeability, stratigraphy, and geological structure, all of which regulate water transmission into deeper layers. In this sense, recharge quantity alone is not a sufficient indicator of groundwater resilience. Several studies have emphasized that geological controls must be explicitly incorporated into recharge assessments, particularly under climate-change scenarios Pandey and Purohit (2022); Letz et al. (2021); Mogaji and Lim (2020). Without this integration, projected recharge may overestimate the effective and sustainable contribution of climate inputs to aquifer replenishment, especially in settings characterised by low-permeability soils or complex geological conditions.

At Amalie Lany, a small location in central Bohemia, the impact of climate change on aquifer recharge shows a decrease in groundwater recharge over 100 years. Significant reduction in aquifer recharge has also been noted in other European latitudes, specifically in the Mediterranean regions. In these regions, groundwater is an important resource due to climate conditions and high water consumption. In addition to these factors, Jyrkama and Sykes (2007) and Santoni et al. (2018) showed that projections and scenarios present the worst future yet: a decrease in precipitation, variability in the recharge potential and changes in interannual climate variability. This situation can be seen in Portugal, where Ferreria (2007) estimated a recharge decrease of 45% in 2007. In Spain also, as described Aguilera and Murillo (2007), the percentage of recharge obtained from precipitation progressively decreased throughout the twentieth century, which may indicate a significant decrease in the available underground resources, as Cárdenas Castillero et al.

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(2021) already had demonstrated in a previous review research.

5. Conclusion

The impact of climate change on long-term groundwater recharge, recharge rates decline significantly as greenhouse gas emissions intensify. Under SSP1-2.6, recharge for BP-I/1 increases slightly (+0.02 mm), indicating some resilience under low emissions. However, as emissions rise, the recharge decreases progressively: SSP2-4.5: -0.07 mm, SSP3-7.0: −0.09 mm SSP5-8.5: -0.13 mm. The decline is even more severe for BP-I/3, with reductions ranging from -0.10 mm (SSP1-2.6) to -0.34 mm (SSP5-8.5), indicating that deeper aquifer layers are more vulnerable.

The results of long-term evaporation anomalies in the Amalie Lany topsoil layer from 1990 to 2090 (first 30 years were analyzed using real physical data and the rest is based on analyses of climate models under different greenhouse gas (GHG) emission scenarios). These results indicate a clear upward trend in evaporation rates. The data show a direct correlation between increased emissions and intensified evaporation, significantly affecting soil moisture retention of groundwater recharge. In low-emission scenarios (SSP1-2.6), evaporation increases modestly from 0.02 mm/day (2020-29) to 0.05 mm/day (2080-89), indicating that even with strong mitigation measures, climate-induced evaporation is still expected to increase. Similarly, in intermediate emissions (SSP2-4.5), the trend intensifies, reaching 0.09 mm/day by 2080-89, showing that moderate emissions lead to a nearly twofold increase in evaporation compared to early-century levels.

In scenarios with high (SSP3-7.0) and very high (SSP5-8.5) emissions, the escalation in evaporation is much more pronounced. Under SSP3-7.0, evaporation anomalies reach 0.11 mm/day by 2080-89, nearly three times the anomaly seen in 2020-29. The most extreme increases are observed in SSP5-8.5, where evaporation anomalies remain persistently high beyond 2050, peaking at 0.11 mm/day from 2070-89, highlighting the severe consequences of uncontrolled emissions.

In particular, the 2060-2069 period appears to be a turning point, particularly in the high- and very-high-emission scenarios, where evaporation spikes significantly. This suggests that increasing global temperatures can

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lead to a threshold beyond which soil moisture loss becomes more rapid and sustained. This research confirms that climate change due to the increase in greenhouse gas emissions produces higher evaporation anomalies, reducing groundwater recharge by intensifying moisture loss from the soil before it can infiltrate aquifers. This correlation can be observed on the following lines:

- Under the lowest emissions scenario (SSP1-2.6), evaporation increased by 0.06 mm/day, while groundwater recharge declined by 0.10 mm (15%) over the study period.
- In the intermediate scenario (SSP2-4.5), evaporation increased to 0.09 mm/day, and recharge decreased by 0.17 mm (26%), showing a more pronounced impact.
- For high emissions (SSP3-7.0), evaporation increased to 0.12 mm/day, corresponding to a significant 0.28 mm (44%) decline in recharge.
- Under very high emissions (SSP5-8.5), the effects were the most severe, with evaporation reaching 0.13 mm/day, contributing to a 0.34 mm (54%) reduction in recharge, the most dramatic decline observed.

The turning point for significant groundwater depletion appears to occur post-2040, when evaporation rates increase sharply, particularly under high- and very-high-emission scenarios. If these trends persist, groundwater resources will be under severe stress, particularly in high-emission scenarios. The loss of recharge 54% under SSP5-8.5 suggests that aquifers may become unsustainable within the next century, leading to potential water shortages, degradation of the ecosystem, and increased reliance on alternative water sources. The consistent increase in evaporation across all scenarios indicates that, even with emissions mitigation, some groundwater depletion is inevitable. However, the extent of damage depends on future climate action.

In general, the findings underscore the critical dependence of aquifer recharge on greenhouse gas emission pathways. Deeper aquifer layers are particularly vulnerable, experiencing the largest deficits in all scenarios. The compounded impacts of reduced recharge and increased variability pose serious challenges for sustainable groundwater management. Increasing evaporation and decreasing groundwater recharge underscore the urgent need for

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climate adaptation and mitigation measures. Reducing emissions can significantly slow the rate of groundwater depletion, as seen in SSP1-2.6, where recharge loss remains relatively low compared to high-emission pathways. Sustainable water management strategies, such as improved land use planning, rainwater harvesting, and groundwater conservation policies, will be essential to counteract rising evaporation rates and maintain long-term water security in the Amalie Lany region.

6. Code and data availability

The datasets, model input files, and code used to generate the results presented in this study are available from the corresponding author upon reasonable request.

7. Author contribution

This research work was prepared by Gustavo Cárdenas Castillero as the first author and Michal Kuraz as the second author. The first author was responsible for developing the research proposal, conducting the literature review, designing and implementing the methodology, selecting and calibrating the climate data, interpreting the results, preparing the illustrations, figures, and tables, drafting the manuscript, and carrying out the required revisions. The second author was responsible for editing the manuscript, reviewing and correcting the methodology, preparing the software, and collecting the soil data.

8. Acknowledgement

The financial support from the European Union's Horizon EUSPA-2022-SPACE Research and innovation actions project Comunidad under the grant agreement No 101131859 is gratefully acknowledged. Likewise, we acknowledge the data support and technical advice provided by the Czech Geological Survey and the Czech Hydrometeorological Institute. We would also like to acknowledge the support of the Georgia Water Resources Institute team for their contribution to the climate scenario downscaling methodology and for their valuable recommendations, particularly Dr. Aris Georgakakos and Dr. El Shariff Husayn.

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