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Managed Aquifer Recharge in Confined Multi-Layer Aquifers: A Scalable Framework for Drought Resilience in Central Europe

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Abstract

Managed Aquifer Recharge (MAR), particularly Aquifer Storage, Transfer and Recovery (ASTR), can enhance groundwater resilience in confined multi-layer aquifers under drought stress. We develop an integrated and scalable framework to assess ASTR feasibility by combining (i) meteorological and groundwater drought analysis using the Standardized Precipitation Evapotranspiration Index (SPEI-12) and Standardized Groundwater Index (SGI), (ii) GIS-based multi-criteria decision analysis (MCDA) for recharge site suitability, and (iii) dynamic assessment of surface-water availability using ecological flow thresholds. Applied to the water-stressed Berlin-Brandenburg region, one of Germany's driest areas, where water supply relies heavily on induced bank filtration and faces emerging deficits. Results show that groundwater levels closely follow climatic conditions, indicating that climate-based drought indices can guide timely ASTR operations. The MCDA identified 62.5 % of the area (2,154 km²) as viable for ASTR. Flow-threshold analysis at 27 gauges showed that high-potential downstream sites could provide mean annual recharge volumes of 1.6-4.3 Mm³, offsetting 6-79% of local extractions. At the catchment scale, total mean annual available recharge is 18.2-23.0 Mm³. Literature-based cost estimates (€0.37–0.51 m^{-3}) are substantially lower than regional drinking-water production costs (€1.80 m^{-3}), suggesting potential annual savings of €23-41 million.

Keywords: Managed Aquifer Recharge (MAR); Aquifer Storage, Transfer and Recovery (ASTR); Confined Multi-layer Aquifers; Drought Resilience; Ecological Flow Thresholds; European sedimentary basins

1. Introduction

For decades, many parts of Central Europe have been considered water-secure, a view that delayed the development of integrated groundwater management strategies (Özerol et al., 2016). However, the severe and recurrent droughts of 2018, 2019, 2020 and 2022 have fundamentally challenged this assumption,

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exposing the vulnerability of groundwater resources under combined climatic and anthropogenic pressures (Brakkee et al., 2022). Rising temperatures, more frequent heat extremes, and prolonged periods of low or no precipitation are now decreasing groundwater recharge and accelerate groundwater depletion (Hellwig et al., 2020; Kosow et al., 2024).

A critical issue emerging across the continent is the growing discrepancy between groundwater extraction and natural recharge. The European Environment Agency estimates that a significant portion of EU river basins experience structural water stress, where total abstraction exceeds sustainable levels (EEA, 2021). In Germany, for instance, total groundwater extraction reached 6.1 billion m³ in 2019, corresponding to over 12% of the average long-term recharge (≈ 48 billion m³/year for 1961-1990) (BGR, 2023). This imbalance is projected to intensify as water demand grows, particularly in densely populated urban centres.

Urban agglomerations such as Berlin and the surrounding Brandenburg region serve as a compelling example of this broader European challenge. While often characterized as a moderately stressed zone, it faces acute water stress driven by rapid urban expansion, high water demand from the metropolitan area, and limited natural recharge capacity (Pohle et al., 2025). At the same time, surface-water inflows are expected to decline by up to 126 Mm³ per year following the phase-out of lignite mining, which previously discharged groundwater into the river and thus served as an indirect water source (UBA, 2023). This combination of reduced supply and increasing demand underscores the urgent need for adaptive water management.

These examples reflect a broader European challenge: how to maintain groundwater resilience under simultaneous climatic and socio-economic stressors. Managed Aquifer Recharge (MAR) offers a technically sound solution to bridge the temporal gap between water availability and demand by intentionally storing surplus water underground for later recovery (Shandilya et al., 2022; Bonilla et al., 2016). However, most MAR applications in Central Europe have historically focused on unconfined aquifers and induced bank filtration, leaving the large potential of confined multi-layer systems largely unexplored (Stefan and Ansems, 2018; Ferencz et al., 2024). The adoption of Aquifer Storage and Recovery (ASR) and Aquifer Storage, Transfer and Recovery (ASTR) in these settings is limited by data scarcity, operational uncertainty, and a lack of transferable assessment frameworks that integrate hydroclimatic variability, recharge feasibility, and environmental flow constraints (Brown et al., 2005; Ross and Hasnain, 2018).

This study addresses this critical research gap by developing a scalable and generalizable framework for evaluating ASR/ASTR feasibility in confined multi-layer aquifers under drought stress. The framework

includes (i) hydroclimatic drought assessment using a comparative index approach (SPEI and SGI), (ii) developing a multi-criteria decision analysis to identify optimal sites for ASTR implementation within a confined multi-layer aquifer system, (iii) determining the available surface water for MAR recharge considering ecological flow-threshold analyses for evaluation of the ASR/ASTR feasibility under drought stress to meet future water demand and enhance drought resilience.

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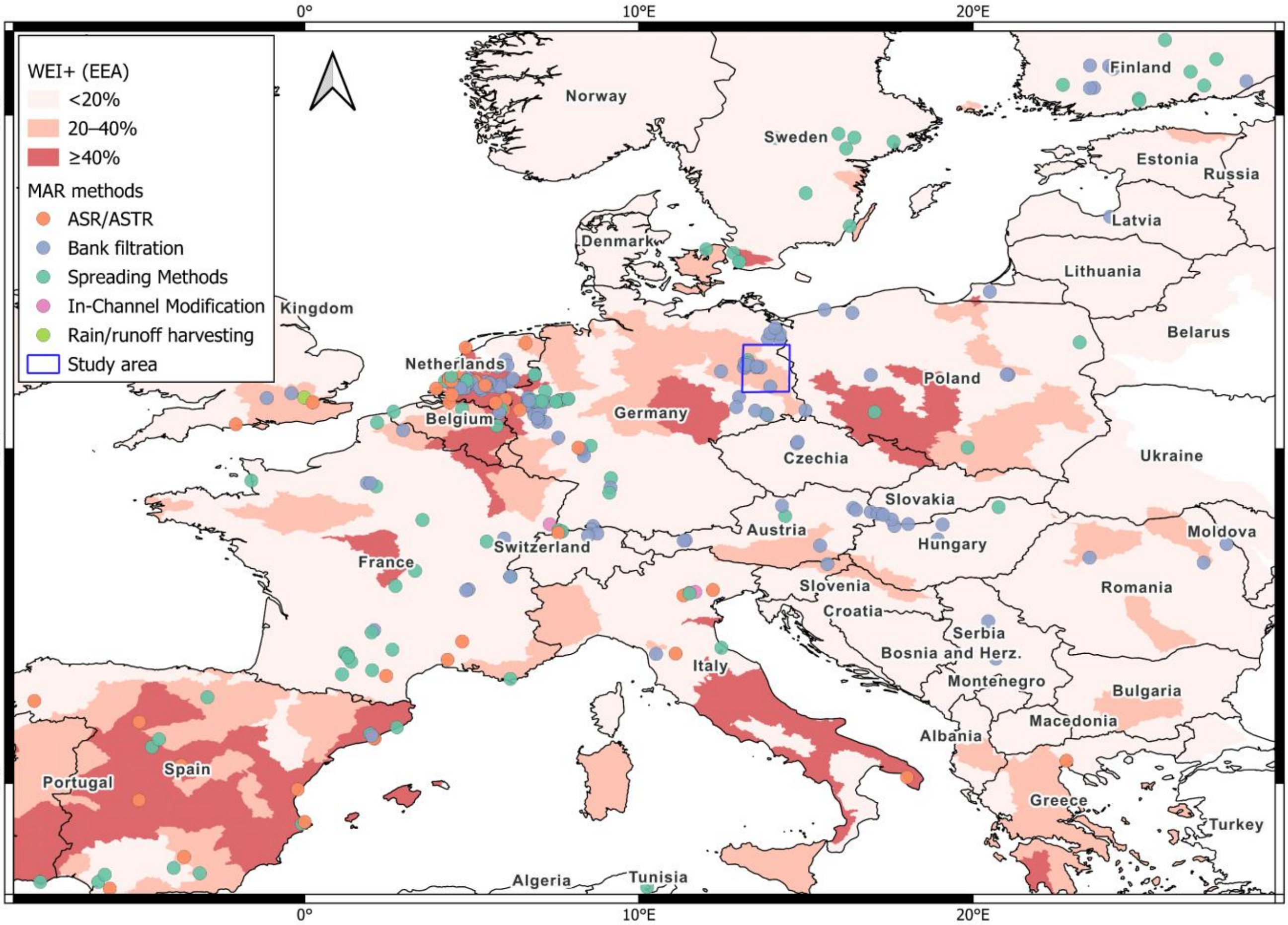

Figure 1. Distribution of MAR methods across Europe, including spreading methods, bank filtration, and ASR/ASTR, highlighting the relative scarcity of ASR/ASTR applications in Central Europe. Background shading indicates water stress levels: moderate (WEI+ 20-40%) and severe (WEI+ ≥40%) (EEA, 2021; IGRAC, 2025; Stefan and Ansems, 2018).

The study area lies within a moderate water stress zone, where induced bank filtration represents an established MAR approach, yet groundwater stress persists (Fig. 1). This gap underlines the need for ASR/ASTR strategies to enhance groundwater resilience in such contexts. By focusing on the methodological framework and drawing broader implications for other European regions with similar hydrogeological conditions, this study delivers broader relevance and contributes meaningfully to sustainable groundwater management and regional water resource planning.

2. Study Area

2.1 Location and Regional Water Stress

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The Berlin-Brandenburg region, particularly its eastern part, is among the driest areas in Germany, with mean annual precipitation ranging from 500 to 700 mm and predominantly sandy soils with low water retention capacity (UBA, 2025b) (Fig. 2a). The study catchment, covering ~3,500 km² southeast of the Berlin metropolitan area (Fig. 3a), has experienced significant hydrological changes, including a ~40% decline in river discharge since 1980, decreased groundwater recharge, and the drying up of many small streams, resulting in a net hydrological water balance deficit that highlights its vulnerability to droughts and increasing water demand (Francke and Heistermann, 2025; Pohle et al., 2025).

2.2 Climate, Hydrology, Soil Types, and Land Use

The study area exhibits flat to gently rolling terrain with numerous lakes and multi-channel river system. Despite abundant surface water, the area experiences chronic water scarcity due to low annual precipitation (averaging 534 to 631 mm/year) and high evapotranspiration (averaging 529 to 673 mm/year) for the period 1991-2020 (Fig. 2b-c). Severe droughts in 2018, 2019, 2020 and 2022 caused record-low groundwater levels, pronounced soil-moisture deficits, and ecological stress (UBA, 2025a; IGB, 2025). Climate projections suggest ongoing warming and increasing drought frequency and duration throughout the 21st century (UBA, 2023, 2025b).

Over centuries, river canalization, groundwater abstraction, and mine-water discharges have altered natural flow patterns and the hydrological balance (Pohle et al., 2025). Groundwater recharge varies spatially, with higher rates in the north than in the south (Fig. 2d), reflecting precipitation, soil type, land use, and evapotranspiration gradients (PIK, 2024). Groundwater level declines exceeding 2 m between 2003 and 2022 have been observed, mainly due to increased drought frequency and rising temperatures (Abdelrahman et al., 2026).

Soils are mainly sandy and sandy loams, with smaller areas of peat and man-made fills (Fig. 2e). These light-textured soils exhibit low water retention capacity, which exacerbates the effects of droughts and reduces infiltration efficiency in some areas (FAO, 1988). Land use is dominated by forests and croplands, interspersed with grasslands and woodlands. Urban areas, industrial sites, mining locations, and infrastructure are concentrated in the northern and central zones, while swamps, peat bogs, and water bodies are scattered (Fig. 2f). This heterogeneous land-use pattern influences recharge distribution and water demand across the area (Barua et al., 2021).

2.3 Geology and Hydrogeology

The catchment lies within the North German Basin, where the subsurface is strongly influenced by repeated glacial and interglacial periods that deposited a heterogeneous sequence of sands, gravels, clays, and tills forming three major aquifer complexes: Aquifer 1 (Shallow) represents largely unconfined Weichselian deposits; Aquifer 2 (Intermediate) consists mainly of confined Saalian sediments and serves as the primary groundwater source; and Aquifer 3 (Deep) comprises deeper Saalian and Tertiary sand deposits, separated by confining tills and clays that restrict groundwater flow, with the Rupelian Clay acting as a regional aquitard protecting the freshwater aquifers from underlying saline groundwater

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(Manhenke et al., 1995; Manhenke, 2001; Lippstreu et al., 2015; Abdelrahman et al., 2026; Fig. 3b). The focus on the confined Aquifer 2 makes this study particularly relevant for ASTR application.

2.4 Water Demand, Supply, and Future Scenarios

The catchment is critical for water supply for the Berlin metropolitan area. In 2024, the Berliner public water utility (BWB) reported supplying 214 Mm³ of drinking water and returned 265 Mm³ of treated wastewater to the hydrological system (BWB, 2024; Fig. 3a). The region faces a dual challenge of supply reduction and demand increase, together amplify long-term water stress and justify the need for MAR/ASTR interventions.

(1) Supply Reduction: The planned coal phase-out by 2038 will remove long-standing mine-water discharges, creating an annual deficit of ~126 Mm³ during dry summers (UBA, 2023). This will exacerbate existing seasonal shortages and constrain the region's capacity to sustain groundwater levels and ecological flows, especially under prolonged drought conditions.

(2) Demand Increase: Regional water demand is projected to rise by around 50 Mm³ by 2050, driven by population growth and the effects of climate change (BWB, 2020; IHK Ostbrandenburg, 2023). This increase is likely to further intensify water stress and compromise overall water security.

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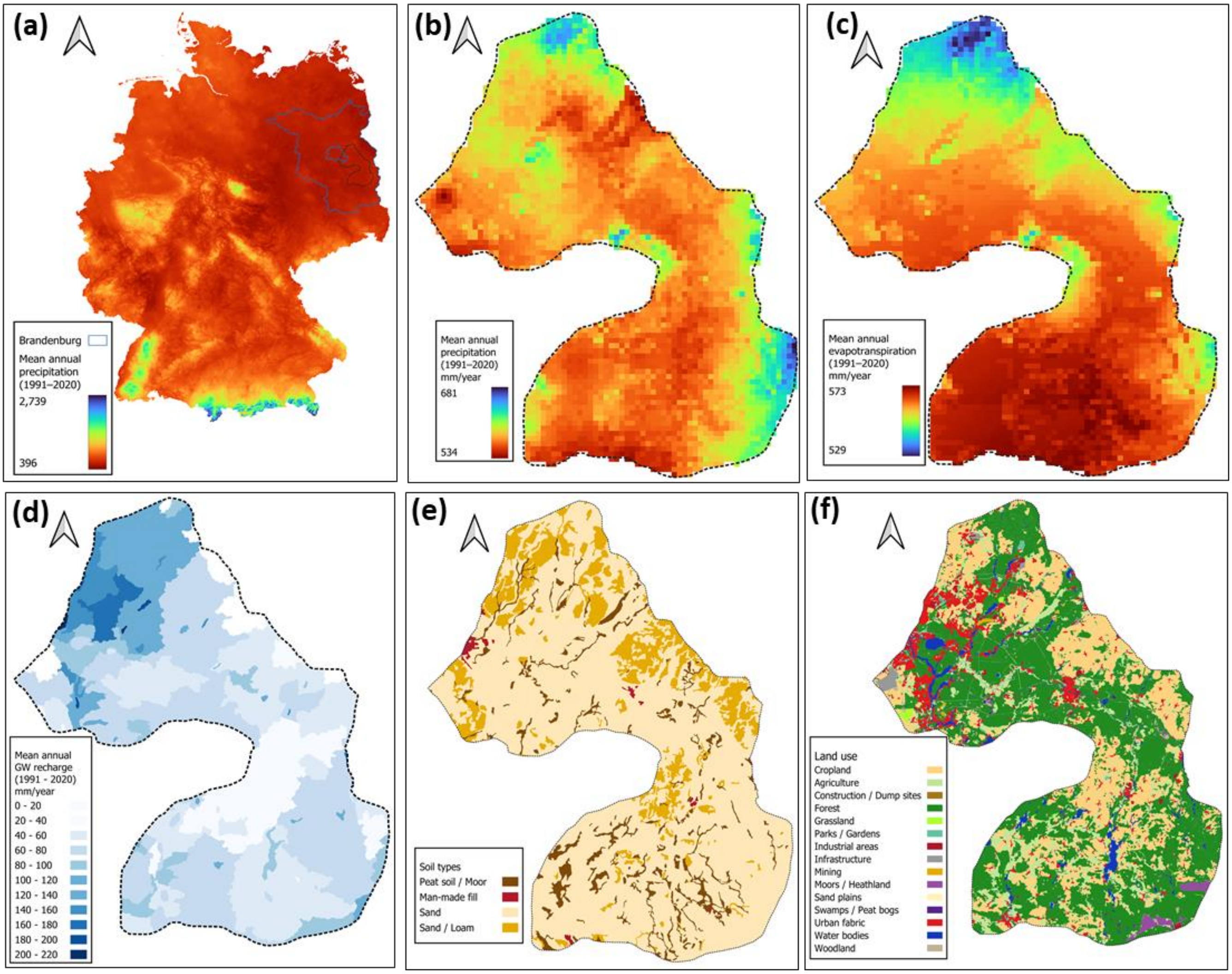

Figure 2. (a) Mean annual precipitation in Germany (1991-2020, German Meteorological Service (DWD), 2024). (b) Mean annual precipitation in the study catchment (1991-2020, DWD, 2024). (c) Mean annual evapotranspiration (1991-2020, DWD, 2024). (d) Mean annual groundwater recharge (1991-2020, Potsdam Institute for Climate Impact Research (PIK), 2024). (e) Soil types, adapted from State Office for Mining, Geology and Raw Materials Brandenburg (LBGR), 2024. (f) Land use, adapted from CORINE Land Cover 2018 (European Environment Agency (EEA)/Copernicus, 2019). All maps were prepared and visualized by the authors.

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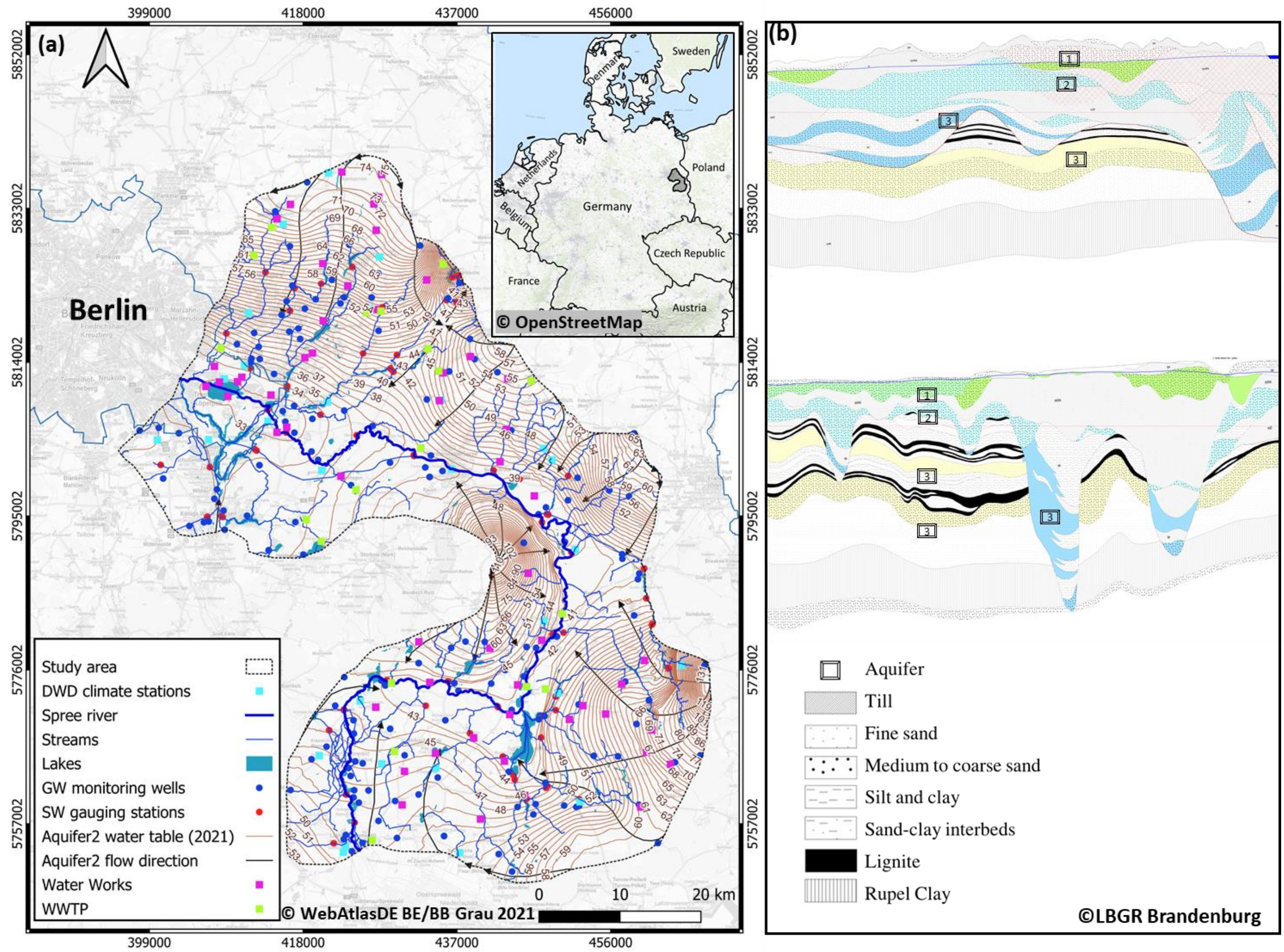

Figure 3. Hydrogeological setting and monitoring network of the study catchment. (a) Overview map showing monitoring infrastructure and key hydrogeological features, including DWD climate stations, groundwater (GW) monitoring wells, surface water (SW) gauging stations, waterworks, and wastewater treatment plants (WWTPs). The map also shows the Spree River, associated streams and lakes, and Aquifer 2 water table (2021) with inferred groundwater flow directions. Base map: © OpenStreetMap contributors, https://www.openstreetmap.org/copyright;©WebAtlasDE BE/BB Grau 2021, https://isk.geobasis-bb.de/mapproxy/webatlasde_2021/service/wms. (b) Representative hydrogeological cross-sections illustrating the stratigraphic framework of Quaternary and Tertiary deposits, including Aquifer 1 (unconfined Weichselian sands and gravels), Aquifer 2 (confined Saalian aquifer, the primary source for regional water supply), and Aquifer 3 (deeper Quaternary/Tertiary aquifers), while the Rupelian Clay serves as a regional aquitard, safeguarding freshwater aquifers from deeper saline groundwater.

3. Materials and Methods

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We compiled a comprehensive dataset of meteorological, hydrological, groundwater, hydrogeological, and water-use records spanning 1980-2024 and applied established drought indices to identify anomalies in both meteorological conditions and groundwater storage, comparing their temporal dynamics to guide the assessment of ASTR suitability. Building on this, the study employs a four-component framework to evaluate the feasibility of ASTR in confined multi-layer aquifers, designed to be transferable across European hydrogeological settings. The framework integrates a hydroclimatic drought assessment through comparative analysis of meteorological and groundwater drought indices; a groundwater stress evaluation using non-parametric indexing of long-term water-level records; a GIS-based site suitability analysis employing multi-criteria decision analysis (MCDA) to determine optimal recharge locations; and surface water availability quantification via dynamic operational assessments of flow variability coupled with ecological flow-threshold analyses.

3.1 Data Sources and Processing

We used precipitation and potential evapotranspiration (PET) from the DWD 1-km gridded datasets (monthly) for hydrological characterization. For drought index computation (SPEI), we used daily precipitation and PET from ERA5 (see Section 3.2). We obtained river and stream discharges, lake levels, and ecological flow thresholds from the State Office for the Environment Brandenburg (LfU, 2024), encompassing approximately 89 gauging stations with daily records.

We obtained groundwater heads from 176 long-term monitoring wells spanning Aquifer 1, 2, and 3 from the LfU. We derived aquifer characteristics, such as thicknesses of the aquifer and unsaturated zone, depth to aquifer tops, confined/unconfined conditions, and lateral extent from a 3D hydrogeological model developed for the region (Abdelrahman et al., 2026).

We compiled historical water use data and future demand projections for agriculture, industry, domestic supply, and waterworks from BWB, Adelphi Research, the Office for Statistics Berlin-Brandenburg (AFS), the German Technical and Scientific Association for Gas and Water (DVGW), the Leibniz Centre for Agricultural Landscape Research (ZALF), and LfU (Adelphi Research, 2025; AFS, 2024; DVGW, 2024; ZALF, 2025; BWB, 2025)

We acknowledge challenges related to heterogeneous monitoring density across aquifers, temporal gaps in some records, inconsistencies in water use reporting, and uncertainties in PET estimates from gridded climate data. Nevertheless, these datasets provide a solid foundation for drought assessment and ASTR suitability evaluation.

3.2 Hydroclimatic and Groundwater Drought Indices

To quantify the severity and propagation of drought, we applied two key indices. We assessed meteorological drought using the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) from daily precipitation and potential evapotranspiration (PET) data for 1980-2024 from ERA5, the fifth-generation global reanalysis produced by the European Centre for Medium-Range

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Weather Forecasts (ECMWF) (Hersbach et al., 2020). The data were aggregated to 12-month accumulation periods (SPEI-12) to capture long-term moisture deficits and surpluses. The index was computed by fitting the precipitation minus PET series to a probability distribution and transforming it into standardized values (mean = 0, variance = 1), where positive values indicate wet conditions and negative values indicate drought.

To quantify groundwater drought, we applied the Standardized Groundwater Index (SGI), a method that converts groundwater levels into a dimensionless Z-score relative to their long-term distribution, effectively identifying below-normal groundwater levels (drought conditions) and above-normal wetness (Bloomfield and Marchant, 2013; Gan et al., 2025; Kumar et al., 2016). The computation involved assembling long-term monthly groundwater-level records for the entire catchment and 21 sub-catchments. A common preprocessing step was to remove non-stationarity, such as seasonal cycles, to isolate purely wet-dry fluctuations (Henao Casas et al., 2022; Brakkee et al., 2022).

Finally, we performed a cross-correlation analysis between the SPEI-12 and SGI time series to quantify the lag time and strength of the relationship, assessing how meteorological drought propagates into the groundwater system.

3.3 Water Balance, Extraction Distribution, and Future Scenarios

We evaluated the spatial and temporal dynamics (1980-2024) of the hydrological water balance, groundwater abstraction, treated wastewater return flows, and future water-demand projections to quantify current pressures and assess prospective deficits across the catchment, distinguishing sectoral uses for domestic, industrial, and agricultural purposes. To assess the historical water balance, we used data from the Soil and Water Integrated Model (SWIM) developed by the Potsdam Institute for Climate Impact Research (PIK) for 1980-2024. This semi-distributed ecohydrological model simulates key components of the water cycle, including precipitation, actual evapotranspiration, runoff, and storage change (Krysanova et al., 2022). We aggregated monthly outputs to annual means and computed the long-term balance for each sub-catchment to delineate zones of surplus and deficit and identify areas with sustained negative water balance, indicating potential recharge limitations.

We estimated future water-demand trajectories (2025-2050) by integrating data collected from BWB, Adelphi Research, AFS, DVGW, and ZALF. Projections were developed under three combined climate-socioeconomic pathways based on the Representative Concentration Pathways (RCPs; van Vuuren et al., 2011; Kreienkamp et al., 2022): RCP 2.6 (sustainability-oriented), in which the Paris Agreement is fully followed with stricter climate policies and a stronger focus on environmentally sustainable approaches; RCP 4.5 (business-as-usual, most likely), representing a development pathway where climate mitigation and economic growth are balanced; and RCP 8.5 (fossil-intensive), characterized by economic development driven by fossil- and resource-intensive production processes. We evaluated sectoral demand across four categories: total waterworks, S1 (agriculture, forestry, and fisheries), S2 (industry and energy), and S3 (services, domestic, and recreation).

3.4 ASTR/MAR Site Suitability (MCDA)

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We applied a GIS-based multi-criteria decision analysis (MCDA) to map the suitability of the study catchment for ASTR implementation, following established MAR/ASTR suitability frameworks (e.g., Khalil et al., 2022; Sharma et al., 2022). We defined six key site-selection criteria (Table 1), using datasets including Aquifer 2 storativity (specific storage × thickness), hydraulic conductivity (K) from the 3D hydrogeological model, depth to Aquifer 2, land-use maps, and river and extraction well locations. We scored criteria from 1 (unsuitable) to 5 (highly suitable) and applied masks for absolute constraints such as water bodies, and Well Protection Zones 1-2.

Aquifer 2 storativity: We calculated Aquifer 2 storativity as the product of specific storage (Ss) and layer thickness (b) (S = Ss × b) to represent actual storage capacity for Aquifer 2. We derived specific storage values from lithology-based estimates within the 3D hydrogeological model and multiplied by the actual Aquifer 2 thickness for each cell. Suitability scores ranged from 5 ($>5\times10^{-3}$) to 1 ($<1\times10^{-4}$).
Hydraulic conductivity (K): We prioritized areas with higher K values, as they allow water to infiltrate and spread more effectively. Suitability scores ranged from 5 (>30 m/d) to 1 (<5 m/d).
Depth to Aquifer 2: We assessed the depth from land surface to the aquifer top, as greater depths increase injection costs. Scores ranged from 5 (highly suitable, <20 m) to 1 (unsuitable, >50 m).
Land Use/Land Cover: We excluded densely urban areas, water bodies, wetlands, and protected natural reserves, favouring forests, open land, and agricultural areas, as they are more likely to accommodate recharge facilities with minimal siting conflicts. Forest scored 5, shrubs/herbaceous 4, cropland 2.
Distance to source water: We considered the distance to the river and its tributaries to minimize pipelines, canals, and costs, while excluding flood-prone areas. We estimated groundwater travel time from recharge areas to source water using particle tracking simulations within the hydrogeological model to prevent rapid return flow that could reduce recovery efficiency or affect the river ecosystem (Pollock, 1994; Harbaugh, 2005; Wang et al., 2020). Sites within 500-800 m scored 5, while those >1500 m scored 2.
Distance to extraction wells: We assessed the proximity of groundwater pumping wells, excluding highly sensitive Protection Zones 1 and 2 to avoid well interference while ensuring effective recovery. We relied on official LfU data on groundwater travel times to pumping wells, which are based on hydrogeological assessments and the delineation of water protection areas. For the remaining areas, we scored suitability according to travel time: <10 years = 5 (highly suitable), 10-30 years = 4, >30 years within the catchment = 3, and outside the catchment = 1 (unsuitable).
We combined all criteria using a weighted overlay, with equal weighting based on literature and expert judgment. We then produced a composite suitability index, rescaled to a range of 0 (Unsuitable) to 100 (Highly Suitable). Finally, we screened high-scoring areas for aquifer volume, source water availability, and location suitability, generating a shortlist of candidate ASTR sites for further evaluation.

Table 1: MCDA criteria and suitability scores for ASTR site selection

Criterion (unit)	Highly suitable	Suitable	Moderately suitable	Low suitable	Unsuitable
	5	4	3	2	1
Storativity (S = Ss × b)	$>5\times10^{-3}$	1×10^{-3} - 5×10^{-3}	5×10^{-4} - 1×10^{-3}	1×10^{-4} - 5×10^{-4}	$<1\times10^{-4}$
Hydraulic conductivity (m/d)	>30	20-30	10-20	5-10	<5

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Depth to Aquifer 2 (m)	<20	20-30	30-40	40-50	>50
Land use/land cover *	Forest	Shrubs, Herbaceous vegetation	-	Cropland	-
Distance to source water (m/d)	500-800	800-1200	1200- 1500	> 1500	250-500
Distance to extraction wells*	< 10 years travel time	10-30 years travel time	>30 years travel time and inside well(s) catchment	-	Out of the well(s) catchment

*Notes: Water bodies, wetlands, and Well protection zones 1-2 were masked as absolute constraints.

3.5 Surface Water Availability and Flow-Threshold Analysis

Streams and lakes provide potential sources of water for MAR/ASTR but any abstraction must be carefully regulated to avoid compromising ecological functions and downstream water users in already stressed hydrological systems (Kocis and Dahlke, 2017; Stein et al., 2021). We assessed surface water availability across the study catchment. From a total of 89 surface water gauging stations, 27 provided sufficient long-term daily discharge records (1980-2024) for a robust analysis. For these locations, we defined available volumes using percentile- and frequency- based thresholds from daily streamflow records (1980-2024) at the gauging stations, with rules that maintain environmental flows and allocate only surplus water (Yarnell et al., 2020; Schmidt et al., 2004; Alley et al., 2022). Therefore, we analysed the interannual and spatial variability of streamflow available for MAR/ASTR across 27 locations to evaluate recharge feasibility. We applied two distinct threshold-based approaches to define MAR-eligible surplus flow while protecting ecological functions and hydrological variability:

Approach 1: A more permissive method that applies a fixed hydroecological flow limit combined with a 20% extraction rule (Alley et al., 2022), aiming to maximize recharge potential. When river flows are at or below the hydroecological limit, no water is abstracted in order to protect minimum ecological flows and meet downstream needs (Vanham et al., 2022; Yarnell et al., 2020). When flows surpass the hydroecological limit, up to 20% of the instantaneous flow can be abstracted for ASTR, ensuring that a substantial portion of the flow remains in the channel for ecological and other uses.

Approach 2: A more restrictive method that limits abstraction to extreme flood peaks, prioritizing the preservation of environmental flows. combines several hydrological and hydroecological thresholds to further refine conditions for abstraction. Under this approach, no water is diverted for ASTR when the flows are at or below the hydroecological limit, at or below the median daily flow, or within the range defined by the 2-year and 5-year flood levels, in order to preserve channel maintenance flows and associated habitat functions (Schmidt et al., 2004; Vanham et al., 2022; Yarnell et al., 2020). Abstraction is only permitted when flows exceed the median daily flow but remain below the 2-year flood threshold, provided that post-abstraction discharge remains at or above the median daily flow or when flows exceed the 5-year flood up to the physical capacity of intake, pretreatment, wells, and pond storage infrastructure ((Yarnell et al., 2020; Alley et al., 2022, Richter et al., 2011) Alley et al., 2022, CEFWG, 2021).

We applied these methodologies (approach 1, and 2) to long-term daily discharge records to quantify the volume, frequency, and reliability of water available for MAR/ASTR. In addition, we compared stream-

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water availability with annual groundwater extraction rates and treated wastewater volumes (Meles et al., 2024; Ulibarri et al., 2021) in four representative stressed sub-catchments to assess their potential impacts.

3.6 Indicative Cost Benchmark from Literature

To provide an initial economic context for the technically viable sites identified, we derived an indicative cost range for ASTR implementation from a review of recent European MAR literature. While a detailed, site-specific economic analysis was beyond the scope of this study, reported costs for well-based MAR schemes, including ASTR, typically range from €0.37 to €0.51 per cubic meter of recharged water, including capital and operational expenditures (Ross and Hasnain, 2018; Sprenger et al., 2017). For comparison, the production cost for drinking water in the region is approximately €1.80 per cubic meter (BWB, 2019). This benchmark is used in the subsequent analysis to discuss the broader feasibility of the proposed ASTR sites.

4. Results

4.1 Hydroclimatic and Groundwater Drought Dynamics (SGI/SPEI Indices)

First, we assessed long-term hydroclimatic conditions to characterize water stress in the region, and we observed a steady rise in potential evapotranspiration (PET) over the 45-year period from 1980-2024 (Fig. 4a), driven by rising air temperatures and higher evaporative demand, which together reduce groundwater recharge (Francke and Heistermann, 2025; Tsypin et al., 2024). Precipitation shows strong interannual variability without a robust long-term trend, but the severe drought from 2018 to 2023 is clearly visible (Fig. 4a). The Standardized Precipitation Evapotranspiration Index (SPEI) time series (Fig. 4b) highlights repeated and intense drought episodes over the last four decades, particularly the severe and prolonged periods of 2018-2019 and 2020-2023, characterized by low precipitation and high evapotranspiration, leading to significant moisture deficits.

The catchment-scale Standardized Groundwater Index (SGI) time series (Fig. 4c) confirms that meteorological droughts propagate rapidly into groundwater deficits. The SPEI-12 time series correlates strongly with the SGI (Pearson correlation r=0.73) without any lag, which shows that climate anomalies of the past 12 months directly affect the current state of the groundwater reserves (Fig. 4d).

At the sub-catchment scale, SGI time series reveal pronounced spatial variability in groundwater drought response. Two representative highly stressed sub-catchments (H1, H2; Fig. 4e-f) and two moderately stressed sub-catchments (M1, M2; Fig. 4g-h) exhibited persistently negative SGI values, often below -1.5, indicating chronic groundwater drought and limited recovery. These areas correspond to zones of high abstraction and align with the most severe negative hydrological water balance, as detailed in Section 4.2. Other sub-catchments with high, medium, and low stress are presented in the Supplementary Materials section.

Overall, the regional SGI shows a gradual long-term decline, confirming an ongoing tendency toward groundwater depletion across the study catchment.

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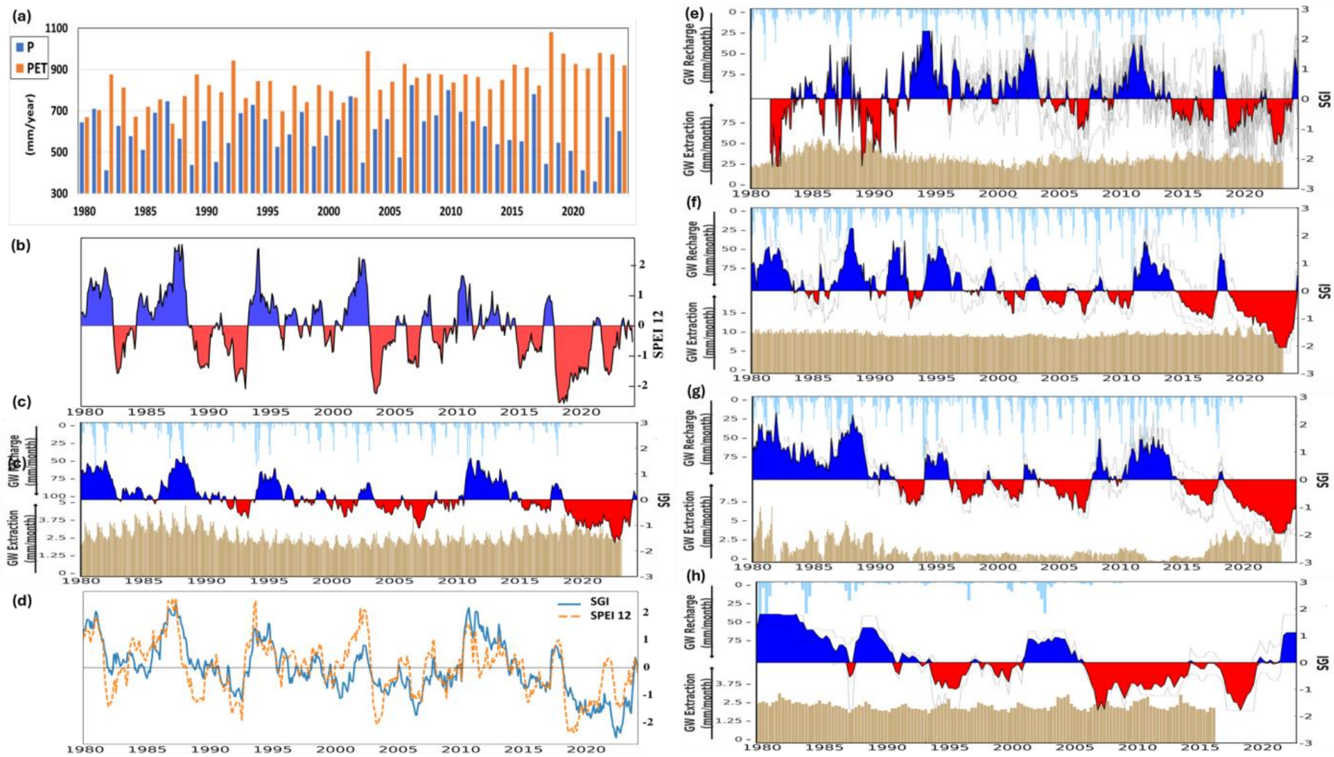

Figure 4. Hydroclimatic and groundwater drought dynamics (1980-2024). (a) Time series of Precipitation (P) and Potential Evapotranspiration (PET). (b) SPEI time series for the entire catchment. (c) SGI time series for the entire catchment. (d) Joint SPEI-12 and SGI comparison illustrating the strong co-variation between hydroclimatic anomalies and groundwater storage response. (e) and (f) SGI time series of highly stressed sub-catchments. (g) and (h) SGI time series of moderately stressed sub-catchments, showing the spatial variability in drought response.

4.2 Water Balance, Extraction Distribution, and Future Scenarios

To get comprehensive information on the water availability, we calculated water balance and regional groundwater extraction pattern. The catchment exhibits a net hydrological water balance of approximately -91.2mm/year, equivalent to a mean deficit of ~319 Mm³/year during 1980-2024. From a climatic perspective (precipitation minus potential evapotranspiration), the deficit increases to -210 mm/year (~735 Mm³/year), highlighting the system's vulnerability to droughts, low river flows, and increasing water demand.

We analysed long-term hydrological data (1980-2024) and observed substantial spatial heterogeneity in the mean water balance across the catchment (Fig. 5a). Negative water balance values dominate the northwestern sub-catchments (H1 and H2), ranging from -154 to nearly -138 mm/year, reflecting persistently higher evapotranspiration relative to precipitation. These areas correspond to zones of intensive groundwater abstraction and lower recharge potential.

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We found that groundwater abstraction is also unevenly distributed across the catchment (1980-2024; Fig. 5b). The highest extraction rates occur in the northwestern sub-catchments, primarily driven by water demand from the Berlin metropolitan area. This spatial pattern highlights the direct link between major demand centres and observed hydrological deficits.

We observed that treated wastewater volumes exceed total groundwater extraction in some northwestern sub-catchments (Fig. 5b). For instance, in the uppermost northwestern sub-catchment (M1), treated wastewater amounts to 13.9 Mm³, compared to 3.57 Mm³ of groundwater extraction. However, in most areas, treated wastewater remains relatively low, ranging from 0.1 to 1.01 Mm³/year per sub-catchment.

We analysed projected water-demand scenarios for 2025-2050 and found a moderate but steady increase in total waterworks demand across all climate scenarios (Fig. 5c). Under RCP 2.6, total waterworks demand fluctuates around 30-31 Mm³, while the most-likely RCP 4.5 scenario shows a modest increase from ~30 to ~32 Mm³ by 2050. Under RCP 8.5, demand rises more steadily to ~33 Mm³ by 2050. The spread between RCP 2.6 and RCP 8.5 (~2-4 Mm³) defines the stress-test range for storage and recovery capacity.
Sectoral patterns exhibit contrasting dynamics. S1 (Agriculture, Forestry, and Fisheries) shows a consistent upward trend in all scenarios, with the strongest increase under RCP 8.5 (from ~5 to ~11 Mm³ by 2050), reflecting higher irrigation needs and landscape water demands under warmer and drier conditions. S2 (Industry and Energy) declines markedly due to improvements in water-use efficiency and structural transitions toward less water-intensive industries. The decline is most pronounced under RCP 4.5 (from ~150 to ~55 Mm³), although RCP 8.5 maintains higher industrial demand (from ~160 to ~110 Mm³). Despite the decrease, S2 remains the dominant contributor to total variance and peak loads. S3 (Services, Domestic, and Recreational Uses) diverges across scenarios: slightly decreasing under RCP 2.6 (~33 to 31 Mm³), gradually increasing under RCP 4.5 (~34 to 37 Mm³), and rising modestly under RCP 8.5 (~33 to 35 Mm³), with pronounced seasonal peaks during summer months. When combined with the expected reduction in in surface water availability due to the planned coal phase-out by 2038 (removing ~126 Mm³/year of mine-water discharges that previously augmented river flow), we project that the catchment will face a significant future water deficit.

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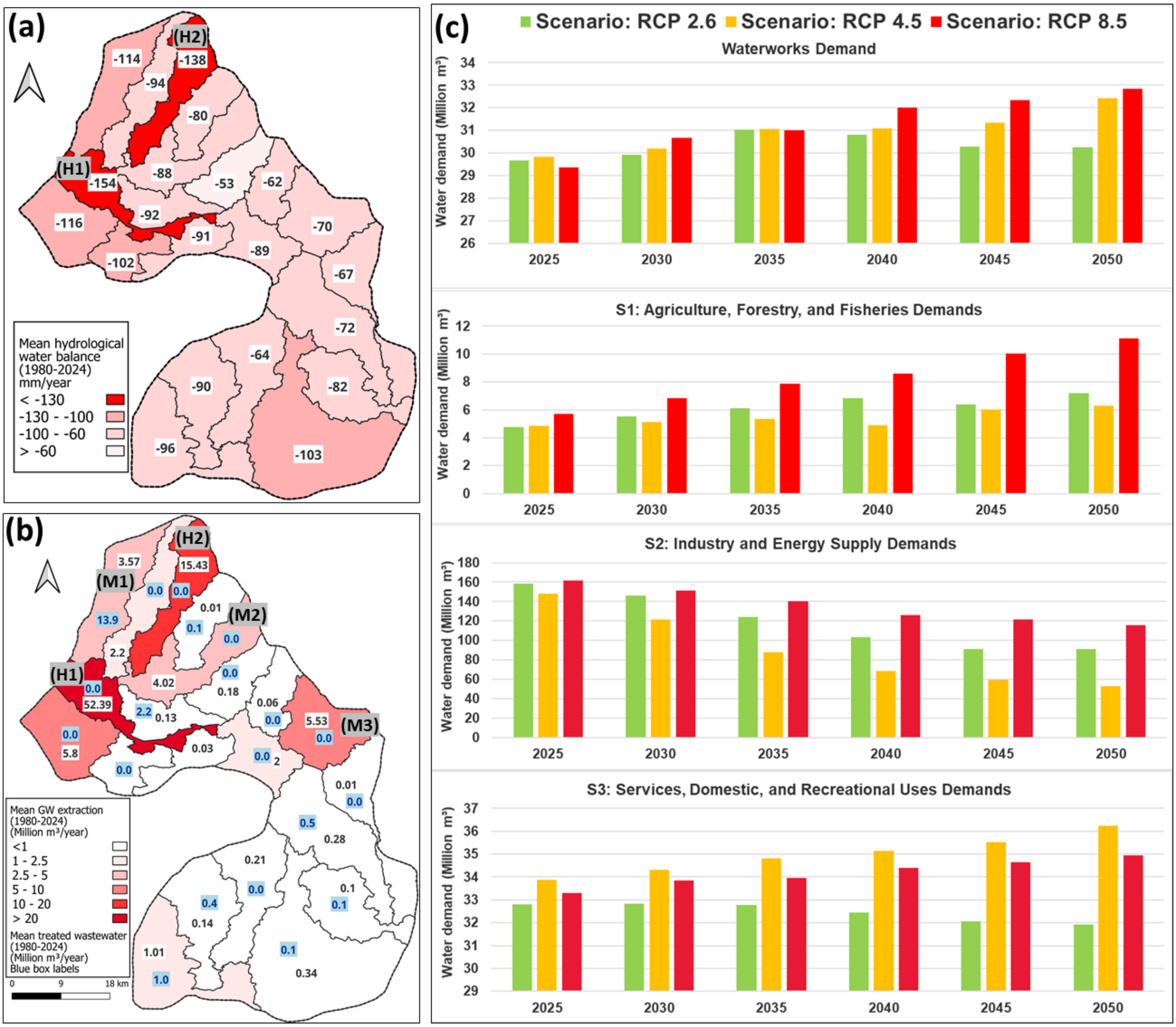

Figure 5. (a) Mean hydrological water balance (1980-2024) across the sub-catchments (mm/year). (b) Spatial distribution of mean annual groundwater abstraction and treated wastewater volumes across sub-catchments (1980-2024). (c) Future water-demand scenarios (2025-2050) showing total waterworks demand and sectoral demands: S1 - agriculture, forestry, and fisheries; S2 - industry and energy; S3 - services, domestic use, and recreation. Raw data obtained from LfU, PIK, BWB, Adelphi Research, AFS, DVGW, and ZALF. Data were processed and visualized by the authors.

4.3 ASTR suitability

We developed an ASTR suitability map using a GIS-based MCDA (Fig. 6). The analysis integrated critical factors into criteria layers, including distance to source water (rivers & streams), distance to

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existing extraction wells, land cover, depth to the target Aquifer 2, Aquifer 2 storativity and hydraulic conductivity (Fig. 4a). Suitability scores were calculated and classified into five classes: very low (0-20), low (21-40), moderate (41-60), suitable (61-80), and highly suitable (81-100). The GIS-MCDA revealed that a significant fraction of the assessable area is suitable for ASTR implementation (Fig. 6b). After masking exclusion zones, 19.5% of the remaining area (670 km²) was classified as highly suitable, and a further 43% (1,484 km²) was classified as suitable. An additional 6% (185 km²) was rated as moderately suitable, while 31.5% (1,086 km²) fell into the low to very low suitability categories. This indicates that a combined 62.5% of the catchment area (2,154 km²) is viable for ASTR. Highly suitable zones are spatially concentrated where Aquifer 2 is relatively thick with relatively higher storativity and hydraulic conductivity, where distances to rivers and production wells are appropriate, and where land-use conflicts are minimal.

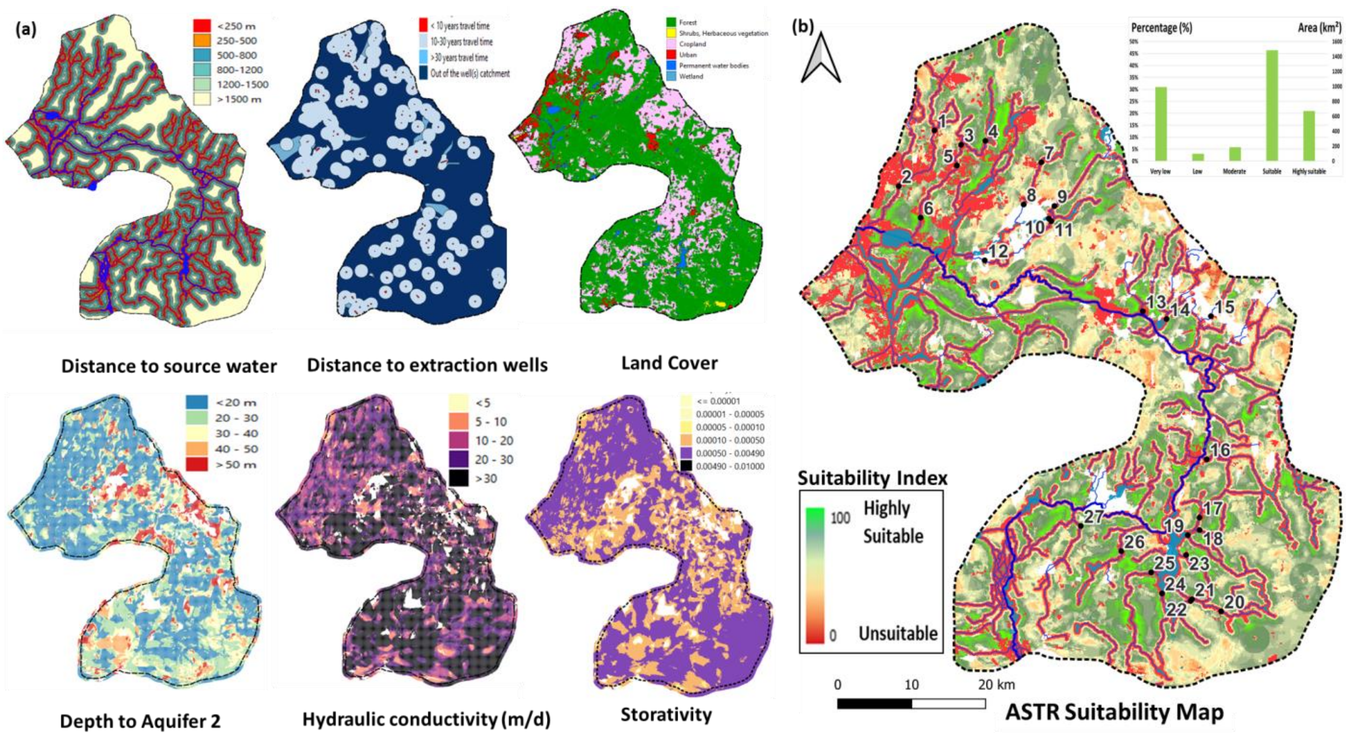

Figure 6. ASTR suitability assessment. (a) Criteria layers used in the GIS-based MCDA. (b) Integrated ASTR suitability map with scores ranging from 0 (unsuitable) to 100 (highly suitable) with a bar chart of the percentage and total area by class.

4.4 Surface Water Availability and Economic Potential

Analysis of daily flow series across 27 surface water gauging sites identified recurring "abstraction windows" or water surplus for MAR, revealing a clear upstream-downstream gradient in potential. Hydrographs for representative sites illustrated how Approach 1 enables sustained abstraction during

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high-flow periods, while Approach 2 limits it to major peaks (Fig. 7). Six representative sites (1, 2, 4, 12, 13, 15) exhibited long, repeatable wet-season windows, whereas low-moderate sites (e.g., 7, 17, 24) offered only short, sporadic peaks that rarely met thresholds.

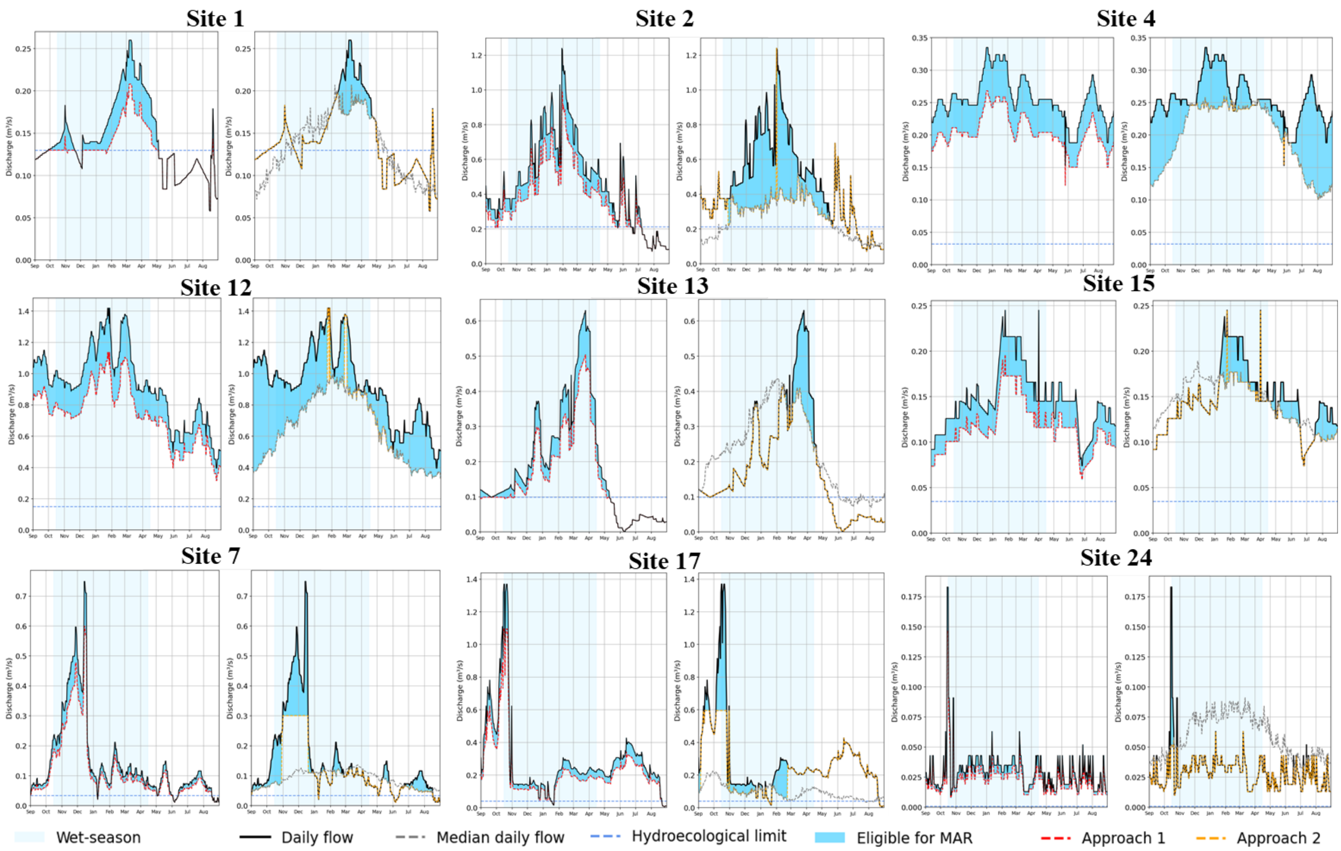

Figure 7. Hydrographs with daily flow, ecological thresholds, and MAR-eligible windows (blue shading) at representative sites; dashed red = Approach 1 (20% rule), dashed orange = Approach 2 (multi-threshold).

We found that the two abstraction approaches revealed a fundamental trade-off between maximizing recharge volume and preserving ecological flows. A comparative analysis of seasonal discharge regimes highlights this operational difference: Approach 1 increases the number and duration of eligible days, while Approach 2 results in a more event-driven capture strategy (Fig. 8).

Site-specific analysis quantified this potential. At the upstream Site 1 (Fig. 8), the mean annual MAR potential ranges from 0.6 Mm³ (Approach 1) to 0.4 Mm³ (Approach 2), equivalent to only 11-17% of groundwater extraction in the local medium-stressed sub-catchment (M1) and 3-4% of the annual treated wastewater volume. Even in the wettest years, maximum MAR values of 1.9 Mm³ (Approach 1) to 1.4 Mm³ (Approach 2) increases this to 39-53% and 10-14%, respectively.

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In contrast, the downstream Site 2 demonstrates significantly higher potential, with mean annual MAR ranging from 1.6 Mm^3 (Approach 1) to 1.9 Mm^3 (Approach 2). These volumes correspond to 45-53% of local groundwater extraction and 12-14% of the annual treated wastewater volume. During high-flow years, maximum MAR values reach 3.8 Mm^3 (Approach 1) to 6.1 Mm^3 (Approach 2), equivalent to 106-169% of annual groundwater extraction and 27-44% of treated wastewater volume, indicating the potential to completely offset, or even surpass, local groundwater withdrawals.

At Site 4, mean annual MAR reaches 1.3 Mm^3 (maximum 2.8 Mm^3) under Approach 1 and 1.1 Mm^3 (maximum 3.4 Mm^3) under Approach 2. These volumes could support a nearby highly stressed sub-catchment (H2), offsetting 9% of its annual groundwater extraction under normal conditions and up to 22% during wet years (Approach 2).

At Site 12, the mean annual MAR is 4.3 Mm^3 (maximum 7.64 Mm^3) under Approach 1 and 3.2 Mm^3 (maximum 9.96 Mm^3) under Approach 2. This capacity could support the highly stressed sub-catchment (H1), contributing 6-19% of its annual extraction, or fully meet the needs of a medium-stressed sub-catchment (M2), covering 79-248% of its groundwater demand.

Sites 13 and 15, considered jointly, show strong potential to support the medium-stressed sub-catchment (M3). The mean annual MAR is 2.1 Mm^3 (maximum 5 Mm^3) under Approach 1 and 1.4 Mm^3 (maximum 4.4 Mm^3) under Approach 2, representing 37% and up to 80% (during wet years) of M3's annual groundwater extraction.

Low to moderate-potential sites (e.g., Sites 7, 17, 24) exhibit severely constrained opportunities, with annual volumes generally remaining below 1.5 Mm^3/year and frequently approaching zero.

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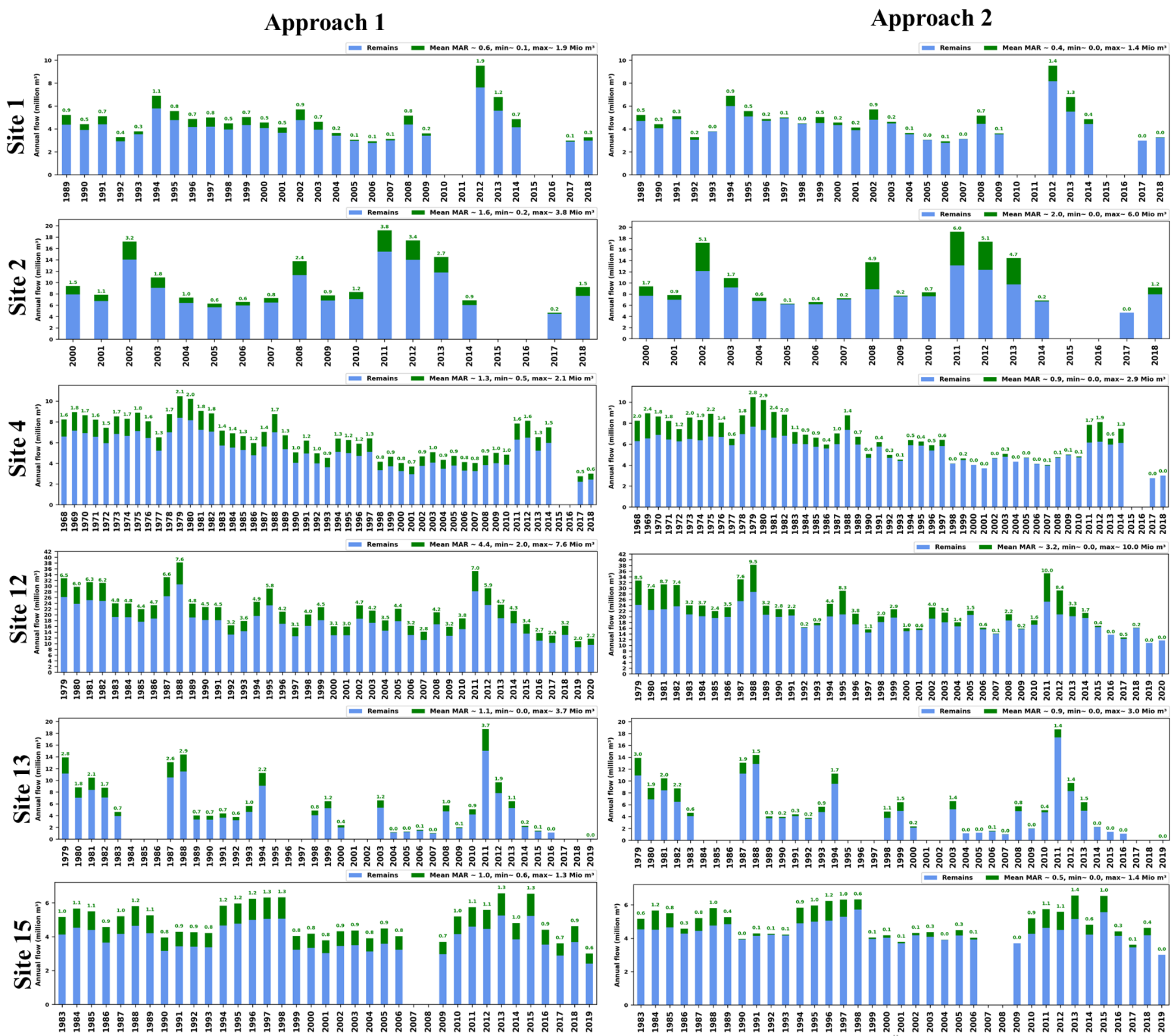

Figure 8. Seasonal discharge regimes and MAR eligibility for Sites 1, 2, 4, 12, 13, and 15 under both approaches, illustrating frequent eligibility under Approach 1 versus event-focused eligibility under Approach 2.

A boxplot analysis across all 27 sites confirmed substantial interannual variability in MAR-available flow (Fig. 9). Approach 1 consistently provides higher median and maximum MAR volumes but exhibits greater variability, making it more productive but less predictable. Approach 2 offers more constrained but potentially more consistent volumes from year to year. The data show that while high-potential downstream sites can yield over 10 Mm³ in wet years, drought years provide little to no surplus across most sites. This underscores that the reliability of MAR is a function of both hydrological variability and the stringency of management thresholds. The spatial integration of these findings is shown in Fig. 10,

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455 which maps streamflow-driven ASTR suitability, highlighting where high-potential surplus streamflow (e.g., at Gauges 2, 4, 12, 13, 15) aligns with stressed sub-catchments (H1, H2, M1-M3).

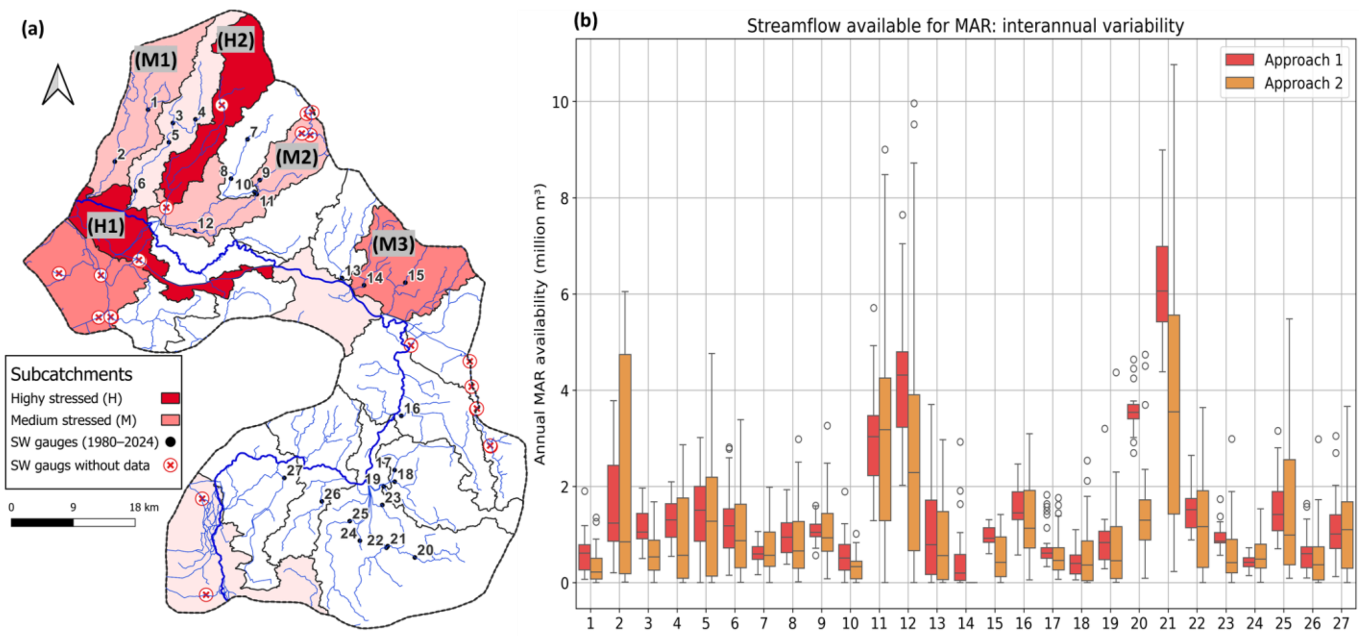

Figure 9. Interannual variability of MAR-eligible streamflow across 27 sites shown as boxplots for Approach 1 (red) and Approach 2 (orange), highlighting differences in central tendency and spread.

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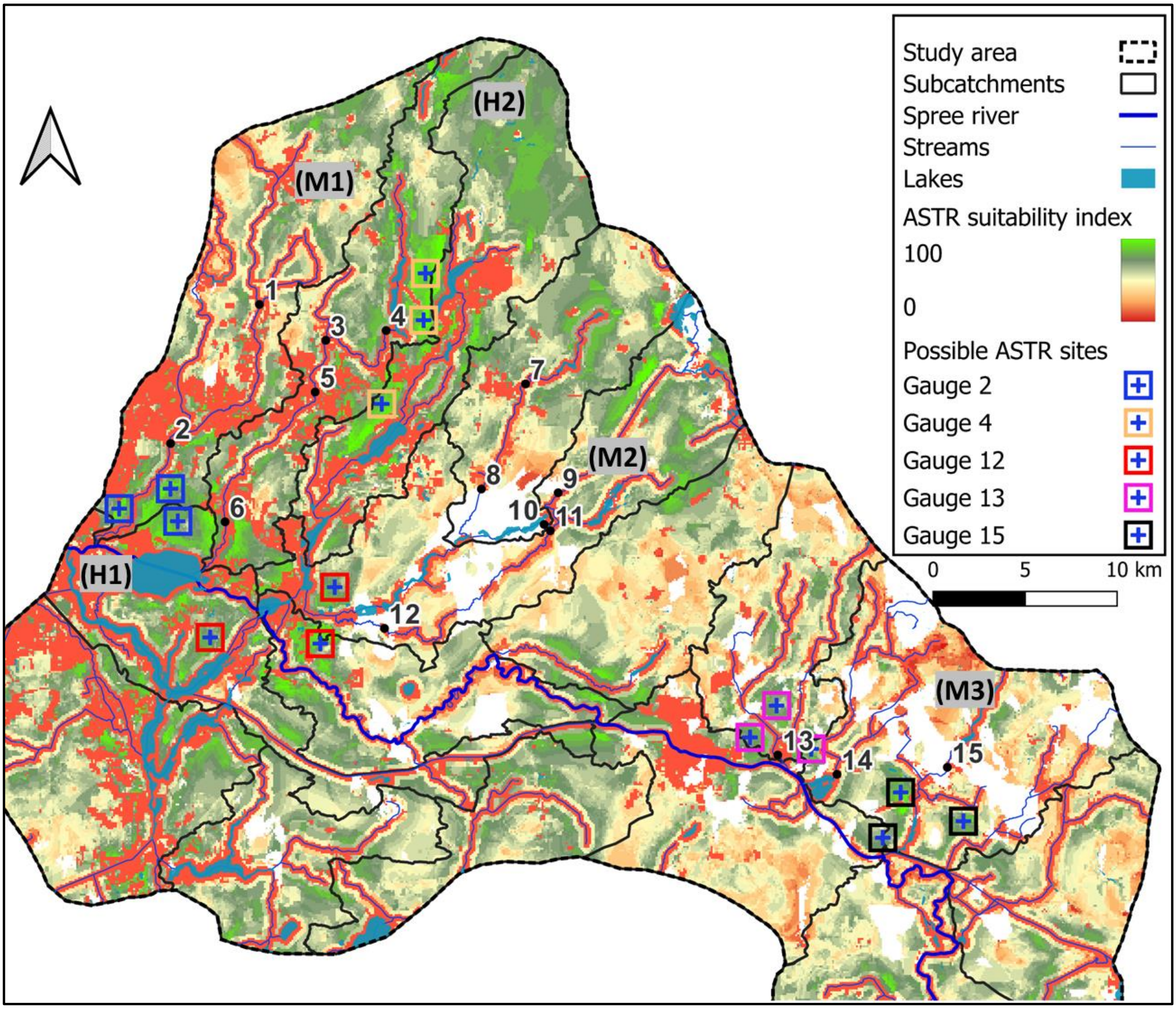

Figure 10. Streamflow-driven ASTR suitability across the catchment, with candidate recharge sites at Gauge 2 (blue), Gauge 4 (orange), Gauge 12 (red), Gauge 13 (pink), and Gauge 15 (dark blue); stressed sub-catchments (H1, H2, M1-M3) are labeled, highlighting where monitored surplus streamflow aligns with favorable hydrogeology for ASTR.

To estimate the catchment-scale potential while avoiding double-counting of stream flows, we selected 18 key sites to represent the cumulative, non-overlapping MAR volume in the Supplementary Materials section. We calculated the total mean annual divertible volume to be 23 Mm³ under Approach 1 and 18.2 Mm³ under the more restrictive Approach 2. During high-flow conditions, these volumes rise significantly

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to 49.8 and 61.9 Mm^3, respectively, highlighting the substantial role of infrequent flood events in recharge strategies.

When we contextualized these volumes using the literature-derived cost benchmark (€0.37-0.51/m^3), the annual investment required to manage the mean annual volumes is estimated at €8.5-11.7 million (Approach 1) and €6.7- 9.3 million (Approach 2). Compared to the cost of producing an equivalent volume of new drinking water (~€1.80/m^3), this represents potential savings of €29.5-41.4 million per year for Approach 1, and €23.3-32.7 million for Approach 2 at the mean annual volume. During high-flow years, these potential savings could increase substantially, reaching up to €89.6 million (Approach 1) and €111.4 million (Approach 2). This significant cost differential underscores the value of ASTR as a cost-competitive drought resilience strategy.

Finally, we note that the 27 gauges analysed represent only about 33% of the surface-water network. This suggests the actual regional MAR potential is likely substantially higher than quantified here, constituting a significant untapped resource for future water management.

5. Discussion

This study demonstrates that a scalable framework integrating drought indices, GIS-MCDA, and flow-threshold analysis can effectively evaluate the feasibility of ASTR in confined multi-layer aquifers. Our findings confirm the technical viability and economic attractiveness of ASTR as a strategic intervention for enhancing drought resilience in water-stressed regions.

The absence of a detectable lag between SPEI-12 and SGI indicates that groundwater levels in this confined multi-layer aquifer system respond almost immediately to climatic anomalies. This rapid coupling has important implications for MAR/ASTR planning. Rather than relying on groundwater signals, water managers can directly use hydroclimatic drought indicators to observe shifts in aquifer storage conditions and implement recharge measures before groundwater stress deepens. In this context, SPEI-12 serves as an early diagnostic tool that captures the evolution of meteorological drought, while SGI confirms its translation into subsurface conditions (Vicente-Serrano et al., 2010; Bloomfield and Marchant, 2013; Van Loon, 2015). Integrating both indices into an ASTR operational framework enables the development of adaptive recharge rules, activating injection during the onset of climatic drought, modulating recharge intensity as groundwater levels respond, and coordinating with surface-water availability assessments. This combined index-based approach strengthens the strategic timing of MAR interventions, ensuring that recharge is aligned with the climate-driven decline in storage and enhancing the effectiveness of ASTR as a drought-mitigation measure in Central Europe's vulnerable confined aquifer systems. The strong correlation between SPEI-12 and SGI underscores that while anthropogenic pressure modulates stress, climate is the primary driver, making ASTR a key climate adaptation tool.

Contrary to the perception that ASTR is only feasible in highly specific hydrogeological settings (Dillon 2015; Page et al. 2018), our GIS-MCDA revealed that 62.5 % of the catchment area (2,154 km^2) is viable for implementation. This substantial potential, identified through systematic criteria like Aquifer 2 storativity and hydraulic conductivity, and strategic proximity to sources and infrastructure, demonstrates

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that suitability is a function of careful site selection. The criteria used are common to many European sedimentary basins, suggesting the framework itself is highly transferable, moving the study beyond a single case towards a generalizable methodology for regional water security planning.

The contrast between the two water-availability approaches, one maximizing recharge and the other prioritizing ecological flow protection, highlights a central management trade-off. High-yield downstream sites (e.g., Sites 2 and 12) provide the most reliable recharge volumes, capable of offsetting over 100% of local abstraction during wet years. This upstream-downstream gradient is critical for prioritizing investments. An adaptive management regime that blends both approaches, applying stricter thresholds during droughts and leveraging flexible rules during wet periods, could optimize the balance between water security and ecosystem protection (Yarnell et al., 2020).

The economic analysis, contextualized by literature benchmarks, reveals a powerful argument for ASTR. The potential savings of €23-41 million annually at the catchment scale under mean conditions, rising to €80-111 million in wet years, demonstrate that ASTR is not just technically feasible but financially prudent. The cost of recharging water (€0.37-0.51/m³) is substantially lower than producing new drinking water (€1.80/m³). This positions ASTR not as a cost, but as a strategic investment that generates significant value by augmenting supply more cheaply than conventional methods, while simultaneously providing the co-benefit of enhanced drought resilience.

While this study quantifies a significant potential, translating this into operational reality requires addressing key gaps. First, the analysis covered only 33% of the surface water network, suggesting the total regional potential is even greater, underscoring the need for expanded hydrological monitoring. Second, pilot-scale projects are urgently needed to validate injection rates, assess geochemical interactions, and refine cost estimates under real-world conditions. Finally, successful implementation hinges on developing robust governance frameworks that define water rights, cost-sharing mechanisms, and adaptive management protocols to ensure environmental and social sustainability.

6. Conclusion

This study presents a scalable framework to assess the feasibility of Aquifer Storage, Transfer, and Recovery (ASTR) in confined multi-layer aquifers. Four central findings emerge.

First, hydroclimatic and hydrogeologic indicators (SPEI-12 and SGI) show that groundwater in the confined multi-layer system responds rapidly to climatic conditions, making climate-based drought indices a reliable guide for timely ASTR implementation.

Second, GIS-MCDA mapping highlights extensive areas suitable for ASTR, underscoring the largely untapped potential of confined aquifer systems in drought-mitigation planning.

Third, ecological flow-threshold analyses show that available surface-water volumes vary with hydrological conditions; although restrictive thresholds limit annual yields, even conservative scenarios provide substantial recharge opportunities.

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Fourth, the economic evaluation suggests that ASTR can deliver cost-competitive performance while helping offset projected water-supply deficits. Collectively, the integrated assessment of drought dynamics, spatial suitability, and water availability establishes a transferable blueprint for similar sedimentary basins across Europe.

Realizing this potential will require pilot-scale trials, enhanced hydrological monitoring, and governance arrangements that support long-term managed recharge. Implementing such a proactive approach can strengthen groundwater resilience, stabilize regional water supplies, and improve preparedness for climatic variability. Overall, the framework developed here offers a solid foundation for strategic planning and sustainable deployment of ASTR in water-stressed regions.

Code/Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

Abdelrahman Ahmed Ali Abdelrahman: Conceptualization, Methodology, Data Analysis, Data Curation, Visualization, Writing (original draft, review & editing).
Hagen Koch: Methodology, Review, Writing (review & editing).
Mobarok Hossain: Methodology, Investigation, Writing (review & editing).
Ronjon Heim: Methodology, Investigation, Writing (review & editing).
Clara Hauke: Methodology, Investigation, Writing (review & editing).
Irina Engelhardt: Conceptualization, Methodology, Data Curation, Supervision, Funding acquisition, Writing (review & editing).

Competing interests

The authors declare that they have no competing interests.

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