Groundwater for Sustainable Development 31 (2025) 101549

Contents lists available at ScienceDirect

Groundwater for Sustainable Development

journal homepage: www.elsevier.com/locate/gsd

Research paper

The potential of localized near-nature managed aquifer recharge in the context of climate change adaption – An assessment within Brandenburg's lower spree catchment

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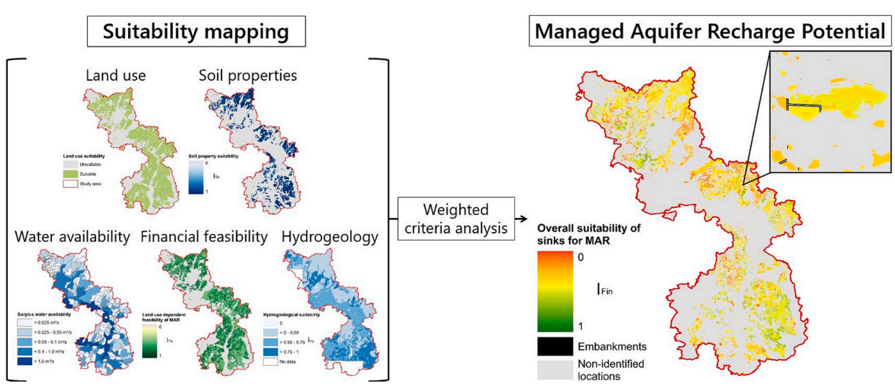
HIGHLIGHTS

- Weighted criteria and thematic layers were used to execute a suitability analysis.
- A potential map revealed locations for surface-induced groundwater recharge.
- A dense net of topographic depressions was identified for near-nature recharge.
- Constructive measures were outlined to enhance the natural potential.
- Many recharge sites can be served with sufficient surplus surface water volumes.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Extreme weather events
Site suitability analysis
Artificial groundwater recharge
Analytical hierarchy process
Surface infiltration
Water sustainability

ABSTRACT

Adaptation strategies are required to strengthen the resilience of groundwater resources that are primarily challenged by climatic and anthropogenic impacts. In this regard, active management through groundwater recharge and recovery techniques known as managed aquifer recharge (MAR) may stabilize groundwater storage and connected surface waters. One option for this management is the surface-induced recharge of available surplus water (infiltration basin), which seeps through the unsaturated soil zone, is stored in an evapotranspiration-free aquifer beneath it, and is recovered when needed. However, surface-induced MAR is underrepresented within the lower catchment of the river Spree. This study therefore assessed potential and individual recharge locations. Including thematic maps derived from a set of weighted criteria, a broad spectrum of suitable conditions were shown using indices in terms of land use, infiltration characteristics, hydrogeology, and economic feasibility. They were consistent with the recharge capabilities found for a dense network of natural topographic sinks, some of which can be employed for decentralized near-natural and semi-constructed groundwater recharge. Accordingly, surplus discharge water volumes from extreme weather events were assessed to be a sufficient source for many recharge locations, including those with storage capabilities that could be increased through construction. Altogether, around one quarter of the study area was found to be

This article is part of a special issue entitled: Managed Aquifer Recharge published in Groundwater for Sustainable Development.
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https://doi.org/10.1016/j.gsd.2025.101549
Received 13 June 2025; Received in revised form 16 October 2025; Accepted 18 November 2025
Available online 21 November 2025
2352-801X/

predominantly moderately to highly suitable, including some isolated and many closely spaced sinks of varying sizes, which can also be used for grouped groundwater recharge. These can therefore be regarded as scalable groundwater recharge clusters and are available for further comprehensive decision-making and model-based analysis.

1. Introduction

In recent decades, Berlin's surrounding area has been affected by complex, multifactorial processes driven by both anthropogenic and climatic impacts (Francke and Heistermann, 2025; Nützmann et al., 2011), which have contributed to extreme pressures on the already scarce soil and groundwater resources (Germer et al., 2011; Holsten et al., 2009). In particular, the dominantly forested landscape of Brandenburg has been subjected to significant transpiration losses (Douinot et al., 2019; Natkhin et al., 2012), while Berlin faces increasing water demand and progressive surface sealing (Frommen and Moss, 2021; Kuhlemann et al., 2020) and consequently lower recharge (Tsypin et al., 2024). Model-based climate projections indicate a rise in temperatures (Cubasch and Kadow, 2019; Dezsi et al., 2018) and potential evapotranspiration (Dezsi et al., 2018; Wiggering et al., 2008), but fail to draw a consistent and unbiased picture of future conditions. The expected circumstances may in fact lead to more frequent extreme weather events that could range from drought (Grillakis, 2019; Spinoni et al., 2018) to heavy rainfall (Hosseinzadehtalaei et al., 2020; Fallmann et al., 2017). The first consequences of this have appeared in recent decades (Caldas-Alvarez et al., 2022; Reinermann et al., 2019) and are unlikely to bring any relief for the water-stressed landscape. The resulting recurrent absence of sufficient groundwater recharge could cause the aquifer system to respond with greater sensitivity (Thomas et al., 2014), disrupting the water supply of groundwater-dependent ecosystems (Steidl et al., 2023; Kleine et al., 2021) and affecting agricultural productivity (Gutzler et al., 2015; Schindler et al., 2007).

Hence, present water resources should be managed wisely to maintain hydrological and ecological functions (Chen et al., 2023) by retaining more water in the landscape (Reyer et al., 2012), while temporal flow-component dynamics (Krause et al., 2007) clearly lead towards the storage and buffer capacities of the aquifer system to be a crucial factor for success (Hellwig and Stahl, 2018). Groundwater recharge in north-east Germany's younger Pleistocene lowlands is characterized by an almost negative climatic water balance (Germer et al., 2011; Holsten et al., 2009) and is mainly controlled by temporal recharge during the winter (Tsypin et al., 2024). The lowlands are further characterized by a dense network of widely distributed topographic sinks of glacial origin (~40 per km^2) (LGB, 2025; Gerke et al., 2010), which can be assumed to have a positive impact on natural groundwater recharge (Vyse et al., 2020; Lischeid et al., 2017). Natural sinks are therefore a legitimate goal for improving groundwater recharge, fostering more resilient groundwater resources.

One way of doing this is an integrated water resources management (IWRM) technique known as Managed Aquifer Recharge (MAR). This involves actively managing water resources based on various groundwater recharge and recovery techniques (Zhang et al., 2020; Dillon et al., 2019), as selectively illustrated above for the regional context (Fig. 1). Available surplus water is applied to the aquifer via surface-induced recharge, by means of seepage through the unsaturated soil zone (e.g., using infiltration basins), by passively siphoning off surface water through a river or lake bank (bank filtration) or by direct injection and recovery at a single well (ASR), or multiple wells (ASTR). The recharged water induced into the aquifer can be stored and transferred without significant evapotranspirative losses for seasonal or annual periods (Page et al., 2023; Dillon et al., 2019) to stabilize subsequent base flows to surface waters (Ronayne et al., 2017) and wells (Bouwer, 2002) during times of increased need. MAR is thus a concept that can be applied to adapt to the present uncertainties of climate change (recharge of heavy rainfall; recovery during drought) (e.g., Henao Casas et al., 2022; Guyennon et al., 2017), but needs to undergo a rigorous site suitability assessment to avoid failure due to clogging, aquifer pollution, or inefficient operation (Zhang et al., 2020).

Accordingly, many GIS-based studies have been carried out to assess whether sites are suitable for MAR, based on a broad set of criteria (Sallwey et al., 2019; Russo et al., 2015) and model-based impact evaluations (Ringleb et al., 2016). However, as those studies have mainly attempted to evaluate individual settings in one or a few selected areas, the results cannot unconditionally be applied to the complex hydrological conditions of the Spree region. Assessment of the regional

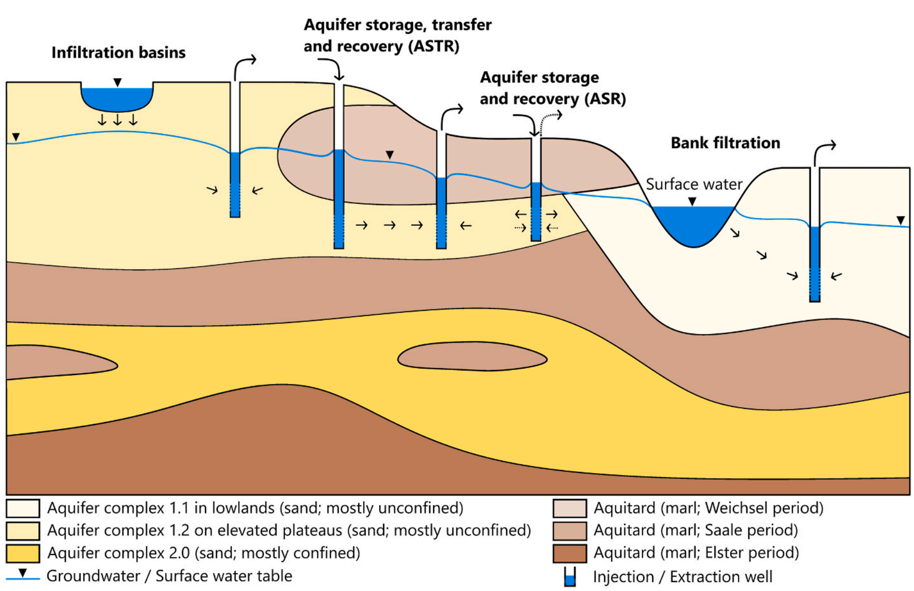

Fig. 1. Schematic illustration of MAR types that can be used in the study area's hydrogeological setting.

MAR potential has been restricted in its range (mostly bank filtration) (Sprenger et al., 2017) and thrown into doubt by the seasonal variability of accessible surface water discharge (Krause et al., 2007), which is mainly limited by the precipitation pattern (Thomas et al., 2012) and ecological minimum discharge (WHG, 2009) during the winter. Thus, centralized large-scale recharge projects may not be sufficient, but could be substituted by a large number of the nature-based recharge points described above (e.g., Beganskas and Fisher, 2017) and served with seasonal and local surplus discharge volumes. Hence, our study aims to help demonstrate the overall regional potential of surface-induced MAR to enhance the process of localized recharge, conserving surface and groundwater resources in the lower catchment of the river Spree. This includes the development of a criteria-based approach to assess how surplus water volumes from extreme weather events can be applied to infiltration recharge points already present in the Pleistocene landscape, some of which are constructed, but most of which are natural.

2. Materials and methods

2.1. Study site

This study focuses on the lower surface water catchment of the river Spree and is located southeast of Berlin in the German state of Brandenburg (Fig. 2). It extends from the Barnim plateau in the north to the northern part of the Spreewald in the south and is a mostly rural area covered by agricultural and forested land (LGB, 2025). With a mean annual temperature of around 8–10 °C and precipitation of less than 600 mm (DWD, 2025), a temperate climate prevails over the glacial Pleistocene sediments (Fig. 1). The latter form a shallow (~10 m), mostly unconfined upper aquifer complex of fluvial sands (Voss and Koch, 2001) within glacial valleys (1.1) and elevated plateaus (1.2) (LBGR, 2025). Beneath are less permeable sandy (Weichsel period) or fine-grained (Saale period) marl and silt aquitards (LBGR, 2025) that connect to a thicker (~20 m), mostly confined second aquifer complex (Voss and Koch, 2001).

2.2. Potential assessment

2.2.1. Approach

A set of criteria was derived from global case studies (e.g., Hussaini et al., 2022; Steinel et al., 2016), reviews (e.g., Sallwey et al., 2019; Russo et al., 2015), and available local data. Unlike other studies (e.g., Fuentes and Vervoort, 2020), this included an inconsistent scale and categorization based on data availability to achieve the highest possible level of detail. All thematic evaluation criteria were thereby assigned proportionally graduated index values up to the best suitability of one and aggregated with respect to overall suitability for surface-induced MAR. Unsuitable locations with an index of zero were excluded, regardless of the presence of other criteria. To support this approach, the Analytic Hierarchy Process method was used to express the relative importance of sub-criteria with regard to their relevance for each thematic index (e.g., Eqs. (1) and (4)) by executing a pairwise comparison and normalization of weighting factors (e.g., Fuentes and Vervoort, 2020; Rahman et al., 2012). The acronyms for the sub-criteria are shown in brackets below. This included assessing the soil's properties (I_{Sp}) regarding general (I_{Su}) and infiltration characteristics (I_{If}) as the basis for identifying and rating topographic sinks (I_{S3}). It was supplemented by thematic assessments regarding potential water sources (I_{W3}), aquifer accessibility (I_{Hy}), and economic feasibility (I_{Fe}) that were equally aggregated to derive an overall suitability index (I_{Fin}).

All these steps were carried out with the software ArcGIS Pro 3.2.2 (ESRI, 2025).

2.2.2. Identification of natural and semi-constructed topographic sinks

Based on the digital elevation model (DEM) provided by the Brandenburg State Office of Land Surveying and Geoinformation (LGB, 2025), the present terrain was filled locally. The resulting filled DEM was then subtracted from the unaltered DEM to outline the spatial and volumetric extent of natural sinks within suitable areas defined below (2.2.3). Offering near-natural recharge solutions, the grid resolution (1 × 1 m) revealed the full spectrum of sinks, including the DEM's potential vertical inaccuracies (max. 0.3 m) (LGB, 2025). The average sink depth

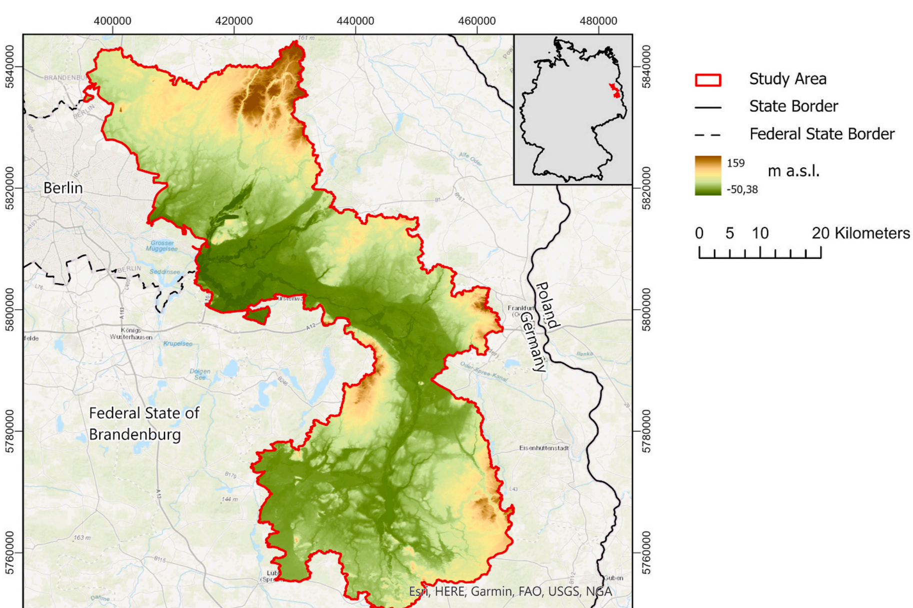

Fig. 2. Spatial orientation and topographic structure of the study area.

was therefore analyzed to sufficiently exceed this threshold in forested areas, but be undercut (~0.1 m) by many agricultural sinks. The sinks in question (≤0.1 m) were thus removed by pre-filling the DEM (0.1 m) locally (e.g., Lidberg et al., 2017), while all others were filtered (>1 m^3).

As they were spatially limited by the prior fit to suitable areas, these natural recharge locations were accompanied by a second enhanced version to allow for spatial extension, including an option for structural modification. The enhanced version comprised sinks with a less restrictive pre-selection of soil property criteria (2.2.3) prior to generation. They were subsequently clipped to fit current land use boundaries (2.2.3; e.g., field or forest paths) to maintain realistic spatial extents. The sinks generated were furthermore only maintained if partially located within the newly extended suitability range (2.2.3; e.g., depth to groundwater 5–7.5 m) to retain the necessary requirements for enlarged sinks. Being clipped to fit the land use boundaries, some natural reservoir boundaries were only partially preserved. These were restored using artificial trapezoidal embankment structures to ensure that they were in line with the maximum filling level and realistic construction geometry (Lehmann, 2021; Casagrande, 1937) of semi-constructed sinks. This included a limited storage height (1.0 m), buffer (0.2 m), and downsizing of exceeding sink, followed by the volume-based rejection (<50 m^3) of sinks.

2.2.3. *Thematic indices for site suitability assessment*

To select suitable areas for surface-induced MAR, basic land use information (LGB, 2025) was taken into account, alongside restrictive zones such as biotopes, moors, large protected areas, water reserves, landscape reserves and nature reserves, and management restrictions set down by the LGB (LGB, 2025) and the Brandenburg State Office for the Environment (LfU, 2025). Only offering a limited nitrate retention potential (Merz et al., 2009), this included a nitrate threshold (50 g/m^3) (e.g., Steinel et al., 2016) to prevent the spreading of contaminants (Bouwer, 2002) based on data from the State Office for Rural Development, Agriculture and Land Consolidation and from the LfU (LELF & LfU, 2025). In extension, waterlogged soils were excluded based on data from Brandenburg's State Office for Mining, Geology, and Resources (LBGR, 2025) since they are usually located on glacial till plateaus (Merz and Pekdeger, 2011) that are less permeable (Voss and Koch, 2001) and associated with hydraulic discharge areas. Correspondingly, only potential recharge areas with adequate storage capacity (Page et al., 2023) and a flow path purification effect (Gale et al., 2002) were favored by a proportional suitability index I_{Su} (e.g., Page et al., 2023; Steinel et al., 2016) (Table 1) for areas with a minimum (7.5 m) regional depth to groundwater (LGB, 2025).

For the enlarged sinks, partially unsuitable settings were accepted and restricted regarding soil contamination prior to generation, whereas a second, less restrictive indexation was applied for the depth to groundwater, as well as the soil properties below (Table 1).

Regardless of the sink type, the soil infiltration properties in the remaining areas were evaluated and indexed (Table 1) based on individually adapted sets of sub-criteria that were arithmetically aggregated for non-agricultural sites (I_{If1}), farmland (I_{If2}), and agricultural grassland (I_{If3}). In combination with general suitability (I_{Su}), as previously assessed, this served to quantify the soil's capability (I_{Sp}) to take up and

Table 1
Categorization and index values that contribute to the thematic soil property index I_{Sp}.

Criteria	Categories		1.	2.	Index
Depth to groundwater	<5	[m]	0	0	I_{Gw}
	>5–7.5			0.13	
	>7.5–10		0.14	0.25	
	>10–15		0.29	0.38	
	>15–20		0.43	0.5	
	>20–30		0.57	0.63	
	>30–40		0.71	0.75	
	>40–50		0.86	0.88	
	>50		1	1	
Field capacity	–	[vol%]	0	–	I_{Fc}
	>52; partly no data		0.03		
	>52; partly <52		0.07		
	>52; partly <39		0.1		
	…		…		
	<13; partly <39		0.93		
	<13; partly <26		0.97		
	<13		1		
Hydraulic conductivity	–	[cm/d]	0	–	I_{Hyc1} & I_{Hyc2}
	<1		0.17		
	<10		0.33		
	<40		0.5		
	40 to < 100		0.67		
	100 to < 300		0.83		
	>300		1		
Soil type	Moor soils (peat)	[−]	0	–	I_{St}
	Clay		0.13		
	Heavy loam		0.25		
	Loam		0.38		
	Sandy loam		0.5		
	Very loamy sand		0.63		
	Loamy sand		0.75		
	Slightly loamy sand		0.88		
	Sand		1		
Hydromorphic state	Groundwater and waterlogging	[−]	0	0.11–0.66	I_{Hm}
	Weak to moderate waterlogging		0.33	0.77	
	Weak waterlogging		0.66	0.88	
	Dominated by seepage		1	1	
Soil water content	Soils with high water content	[−]	0	0.11–0.66	I_{Wc}
	Slightly dry soils		0.33	0.77	
	Moderately dry soils		0.66	0.88	
	Very dry soils		1	1	

pass on water to the aquifer below (Eq. (1)), whereas the infiltration efficiency's impact was prioritized with regard to the sufficient storage capacity already ensured by a minimum depth to groundwater (Table 1).

$$I_{Sp} = I_{If1,2,3}{*}0.80 + I_{Su}{*}0.20 \;\; with \;\; I_{Sp} = 0 \;\; if \;\; I_{If1,2,3} \; or \; I_{Su} = 0 \qquad \text{(Eq. 1)}$$

Accordingly, related soil type properties defined by the LBGR (LBGR, 2025) were analyzed regardless of the type of land use, to prioritize high infiltration rates (Alam et al., 2021; Rahman et al., 2012) as anti-proportionally represented (I_{Fc}) by the soil's water holding capacity (field capacity 1 m). For non-agricultural sites, this was coupled with the hydraulic conductivity at a depth of one (I_{Hyc1}) and two (I_{Hyc2}) meters, to depict the infiltration rates at full saturation (Touma et al., 2007). Meanwhile, more precise data on the agricultural soil valuation (BonaRes Data Centre, 2025) were indexed (I_{St}) regarding the soil type's related infiltration rates (e.g., García-Gutiérrez et al., 2018; Arrington et al., 2013) at farmland and grassland sites. These data were supplemented by hydromorphic development states within the soil profile (LBGR, 2025) whose characteristics resulted from the influence of different soil and groundwater contents associated with either waterlogging or seepage-dominated conditions (Amendola et al., 2018). This made it possible to derive the preferred depth to groundwater and topographic setting (Yurova et al., 2021) of seepage-dominated soils (I_{Hm}). The soil valuation data were used to favor dryer grassland locations (BonaRes Data Centre, 2025) with an increased initial infiltration rate in relation to low initial soil water contents (I_{Wc}) (Anderson et al., 2009; Lili et al., 2008). The latter's dependence on groundwater table rise (Zhang and Schilling, 2006) only applied up to the surface (Youngs et al., 1996), but remained valid in the context of a low aquifer storage capacity.

Within the outlined hydrogeological framework (LBGR, 2025), this was represented by the highly conductive near-surface aquifer complex on elevated plateaus (1.2) and glacial valleys (1.1) (Table 2) that favor the surface-induced infiltration and recovery of water (Fuentes and Vervoort, 2020). The discharging character of the latter (1.1) was considered of lower suitability (I_{Hy}), but still beneficial in the case of outcropping at the surface (Russo et al., 2015), whereas opposing concerns were raised for elevated units (1.2) covered by less permeable layers (LBGR, 2025). Hence, uncovered units with recharge characteristics (1.2) (Merz and Pekdeger, 2011) were considered best, but of relatively low spatial distribution (LBGR, 2025), which is why less conductive absent aquifer or near-surface aquitard units were also considered least.

Regardless, the water supply of all reservoirs required data from the LfU (LfU, 2025) to select extraction points along surface water streams and lakes with a minimum distance to inhabited areas of the land use defined previously (LGB, 2025). These were rated based on the shortest distance to each sink (Table 2). This included the restriction of sensitive surface runoff or groundwater-fed lakes without a connection to streams (Kaiser et al., 2015) and comprised the negative cost and transport-infrastructure-related impact of longer distances (Fuentes and Vervoort, 2020).

In extension, model-based (ArcEGMO) discharge values

Table 2
Categorization and assigned values for the thematic indices I_{Hy}, I_{Fe}, I_{W1}, I_{W2}, I_{S2}.

Criteria	Categories			Index	
Hydrogeological unit	Uncovered aquifer 1.2		[−]	1	I_{Hy}
	Uncovered aquifer 1.1 & covered aquifer 1.2			0.75	
	Absent aquifer complex 1			0.5	
	Surface waters & mining sites			0	
Land use type & agricultural soil quality	Ag	100	[−]	0	I_{Fe}
	Ag	99		0.01	
	…	…		…	
	Cf; Ag	50		0.5	
	…	…		…	
	Mf; Ag	27*		0.73	
	…	…		…	
	Df; Ag	4		0.96	
	…	…		…	
	Ag	1		0.99	
	Co; Ag	0		1	
Construction efficiency	>1000		[m]	0.05	I_{W1}
	901–1000			0.1	
	801–900			0.2	
	701–800			0.3	
	601–700			0.4	
	501–600			0.5	
	401–500			0.6	
	301–400			0.7	
	201–300			0.8	
	101–200			0.9	
	0–100			1	
R_V	$V_{mean\ d} < V_{Sink}$		[m^3/m^3]	$V_{mean\ d}/V_{Sink}$	I_{W2}
	$V_{mean\ d} > V_{Sink}$			1	
Construction efficiency	$0 \leq R_C < 1$		[m^3/m^3]	0.05	I_{S2}
	$1 \leq R_C < 2$			0.1	
	$2 \leq R_C < 3$			0.2	
	$3 \leq R_C < 4$			0.3	
	$4 \leq R_C < 5$			0.4	
	$5 \leq R_C < 6$			0.5	
	$6 \leq R_C < 7$			0.6	
	$7 \leq R_C < 8$			0.7	
	$8 \leq R_C < 9$			0.8	
	$9 \leq R_C < 10$			0.9	
	$R_C \geq 10$			1	

Co = Copses and other vegetation; Df = Deciduous forest; Cf = Coniferous forest; Mf = Mixed forest.
Ag = Agricultural land; Sq = Soil quality points for Ag, with * = Average Sq.

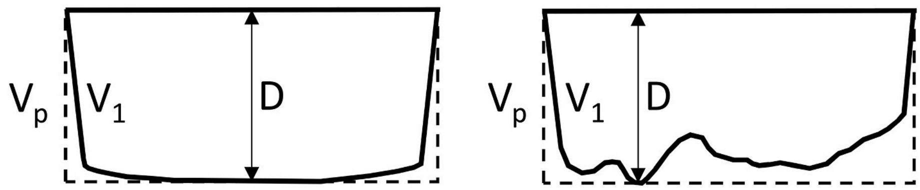

Fig. 3. Schematic illustration of the sink volume V_1 relative to the potential volume V_P for a sink with an index (I_{S2}) close to one (left) and a sink with a relatively low index (I_{S2}) (right).

(1991–2020) from the Office for Applied Hydrology (BAH, 2023) revealed the annual mean daily discharge (Q_{mean}) to be greater than the LfU's minimum environmental flow (Q_{mev}) for almost two-thirds of the assessed stream segments (LfU, 2025). Q_{mev} was thus considered the threshold to define available surplus discharge volumes, but was substituted by Q_{mean} if absent for stream segments (46 %).

In both cases, the resulting annual excess volumes (V_{year}) and days of occurrence ($D_{V\ year}$) were counted to derive (Eq. (2)) the mean daily

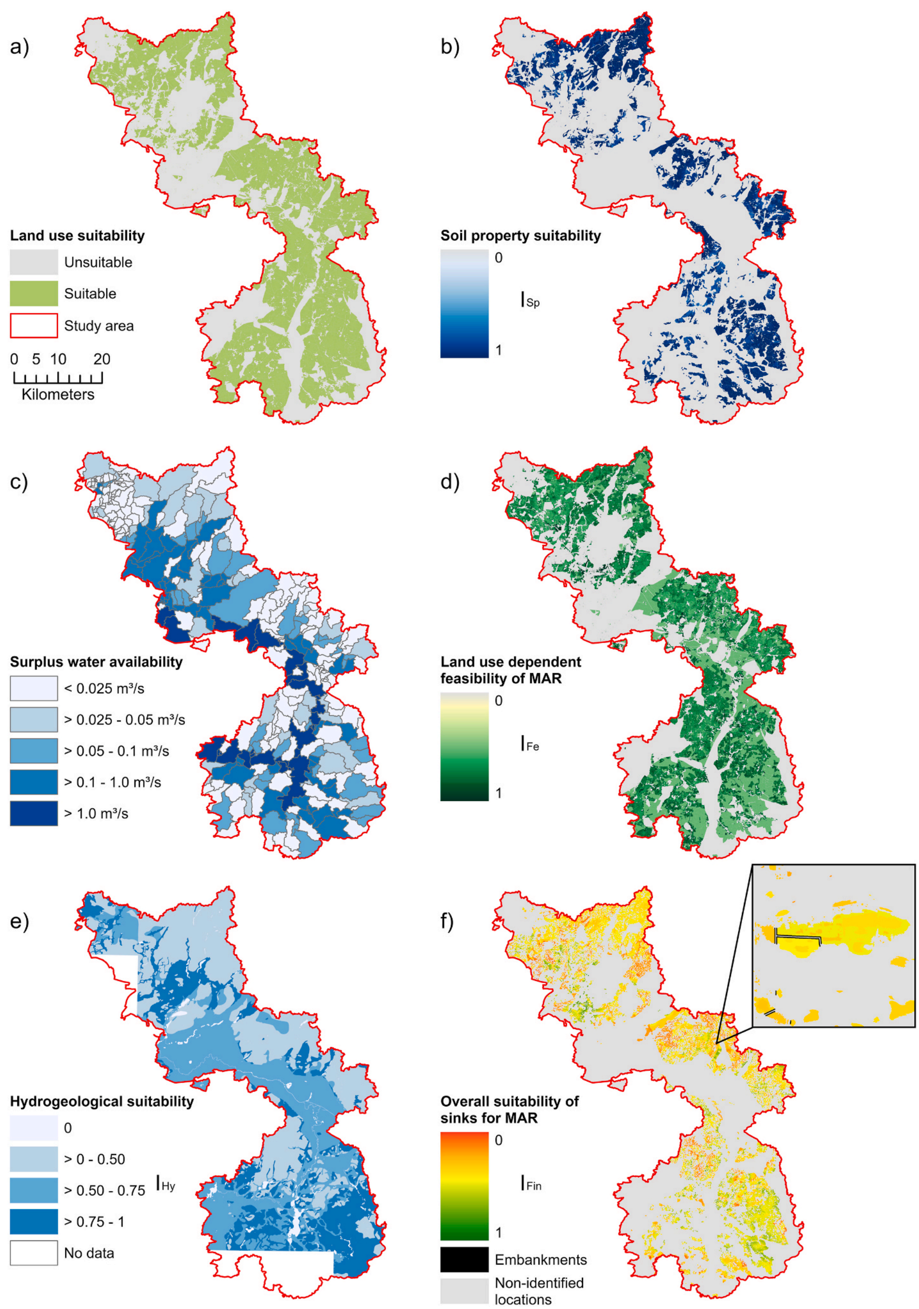

Fig. 4. Assessed suitability for surface-induced MAR regarding land use (a), the soil properties index I_{Sp} (b), the availability of surplus water volumes (c), the land-use-dependent economic feasibility I_{Fe} (d), the accessibility of near-surface aquifers I_{Hy} (e) and the final assessment result for each sink based on the index I_{Fin} (f). The latter includes a more detailed view on examples of the spatial enlargement of sinks with embankment structures.

surplus volume ($V_{mean\ d} > Q_{mev}$ or Q_{mean}) in association with the sink's volume (V_{sink}). The resulting mean filling ratio (R_V) (Eq. (3)) indicated the quantitative suitability (I_{W2}) during days of surplus discharge (Table 2), whereas multiple fillings per day ($I_{W2} > 1$) were not considered with respect to the infiltration dynamics.

$$V_{mean\ d} = \sum_{1991}^{2020} V_{year} \Bigg/ \sum_{1991}^{2020} D_{V\ year} \quad \text{(Eq. 2)}$$

$$R_V = V_{mean\ d} \ / \ V_{sink} \quad \text{(Eq. 3)}$$

Nevertheless, the mostly precipitation-controlled surplus discharge (Thomas et al., 2012; Krause et al., 2007) and consequent I_{W2} may be overestimated due to infrastructural limitations and more conservative environmental thresholds, and is thus assigned a lower contribution factor (0.3) to I_{W3}. By contrast, the distance-related index (I_{W1}) was considered more limited (0.7) by earlier restrictions regarding more distant and elevated recharge sites (Eq. (4)).

$$I_{W3} = I_{W1} * 0.7 + I_{W2} * 0.3 \quad \text{(Eq. 4)}$$

Also representing structural limitations during temporal surface water storage and subsequent recharge, the spatial suitability of the identified sinks (I_{S1}) was rated based on the surface area (A) and useable volume (V_1) (Eq. (5)). Expressed by I_{S1}, the index represents the positive correlation of the pressure head and infiltration rate (Bouwer, 2002) and was preferred to be high.

$$I_{S1} = V_1 \ / \ A \quad \text{(Eq. 5)}$$

$$I_{S2} = V_1 \ / \ V_P \ \ with \ \ V_P = A * D \quad \text{Eq. 6}$$

Accompanied by the index I_{S2}, the actual sink volume (V_1) was compared to a potential volume (V_p) derived from the surface area (A) and maximum useable depth (D) relative to the sink's filling level and lowest point (Eq. (6) & Fig. 3). The resulting efficiency of the useable volume per area and smoothness of the sink lowering/water distribution during the filling process (Fig. 3) was summarized with the first index using the arithmetic mean (I_{S3}).

For sinks enlarged through construction, I_{S2} was substituted based on the indexed construction efficiency ratio (R_C) of embankment material (V_C) and the volumetric difference of sinks enlarged through construction (V_E), and summarized volume of all associated natural sinks (V_N) (Eq. (7)).

$$R_C = (V_E - V_N) \ / \ V_C \ with \ R_C = 0 \ \ if \ \ V_C = 0 \quad \text{(Eq. 7)}$$

Both mostly natural basin types are nonetheless expected to have low energy and maintenance requirements such as pre-treatment (e.g., sediment retention basins) (Steinel, 2011), to maintain high infiltration rates (Pavelic et al., 2011). Taking into consideration the pumping infrastructure and constructed sink alterations (I_{W1}; I_{S2}), financial feasibility is thus mainly associated with size-related initial costs (Ross, 2022; Ross and Hasnain, 2018) for the re-designation of land over time. Hence, unprofitable vegetation such as copses was considered most suitable, whereas agricultural land (Ganot and Dahlke, 2021; Ghasemizade et al., 2019) or forested areas (Tulik et al., 2020; Natkhin et al., 2012) remain affected by fluctuating groundwater tables, which can lead to yield losses. Since financial feasibility is expected to decline with distance (Bouwer, 2002) and is difficult to quantify (e.g., Reyer et al., 2012), the indexation (I_{Fe}) was based on mean yield losses (Table 2) for coniferous forests (110 EUR/ha/year) and deciduous forests (1 EUR/ha/year) (Möhring and Rüping, 2008). By contrast, the mean field and grassland yields (75 EUR/ha/year) calculated by Brandenburg's Ministry of Agriculture, Environment and Climate Protection and LELF (MLUK, LELF, 2022) were positively correlated (Hüttel et al., 2014) with the soil valuation's quality points (BonaRes Data Centre, 2025).

3. Results

The land use assessment revealed an area of around 1464 km^2 (48.07 %) to be generally suitable for MAR (Fig. 4 a). The majority consists of agricultural land (56.64 %) with diverse cropping (50.15 %), grassland (6.33 %), and other uses (0.16 %). The second largest share contains coniferous (33.60 %), mixed (7.98 %), or deciduous forests (1.34 %), whereas the remaining suitable fraction (0.44 %) comprises a small amount of unmanaged vegetation. Building on that, an additional 26.19 % were excluded based on general suitability and soil properties (I_{Sp}) considerations, leaving 666.39 km^2 (21.88 %) suitable for MAR. Further discretized to range between 0.27 and 0.99 (I_{Sp}), mostly medium to good conditions were mostly revealed above a peak of 0.57 were revealed (Fig. 4 b) without relevant land-use-associated differences. Subsequently, locations of general suitability were taken into account to identify 80891 natural sinks, most of which majorly feature a depth-distribution between 0.10 and 0.50 m (e.g., Fig. 4 f). The most prominent fraction (0.11 m) and subsequent almost exponential decline leads to low counts for any depth greater than 0.50 m, regardless of the land use type. However, forested locations occasionally comprise sinks of greater depth (up to 13.31 m) than agricultural sites (up to 5.70 m), as reversely observed for their area (3–190,735 m^2) and useable volume (1–81540 m^3). Yet, the majority of the sinks only lie within the lower range ($\leq$100 m^2 & $\leq$ 30 m^3) and mostly comprise less than two-digit counts for greater properties.

By adapting the soil property criteria, 24367 sinks were spatially extended or newly added without constructed alterations (e.g., Fig. 4 f). This involved a comparable but slightly positively shifted property scheme that includes an increase in the area (49–73 m^2) and volume (3–4 m^3) for the upper 50 % of all sinks. Compared to the associated original sinks, this corresponds to a gain of 1–165540 m^3 and increased maximum volume (165540 m^3), whereas most sinks only gained up to 50 m^3. Regardless of the land use, this is also expressed by a similar relative index distribution of mostly low average depth (S_1), medium exploitation ratio of the potential volume (S_2), and relatively low total suitability (S_3) for natural sinks (Fig. 5a–c) and naturally enlarged sinks (Fig. 5d–f). Nevertheless, slight benefits of the criteria adaptation are expressed by S_2 and consequent S_3 values that were closer to one, as well as a better overall proportional presence of the medium and upper range.

However, the original extent and storage capacity of 8515 unclosed basin fractions could only be restored by outlining potential constructed embankment lines to counteract the partitioning of crossing pathways and other land use restrictions (see Fig. 4 f). This results in a depth of up to 0.50 m for most sinks, including a shifted peak (0.17 m) followed by a second (1.00 m), and sufficient presence up to 1.50 m and likewise improved index (S_1) representation (Fig. 5 g).

Similarly, the maximum and majorly covered area (50 % > 813 m^2; max. 226453 m^2) and volume (50 % $\geq$ 120 m^3; max. 243609 m^3) also benefit from significant gains (50 % $\geq$ 100–1265 m^3 and tenfold area). In this regard, the most commonly occurring volume (4 m^3) equals the volume of the majority of naturally enlarged sinks but only represents the lower spectrum (S_2) with a partly (38 %) insufficient construction efficiency ($R_C \leq 1$), but no recorded negative impacts (RC < 0) (Fig. 5 h). Instead, the overall distribution shows a mostly positive impact ($R_C >$ 1.66). This includes a noteworthy presence (15 %) of efficiency ratios equal to or greater than 10 cubic meters of gained sink volume per cubic meter of embankment material used ($S_2 = 1.00$). Thus, S_3 illustrates a more balanced index distribution, indicating an enhancement of the natural sink potential (Fig. 5 i).

To make use of all sinks for MAR, approximately 923 out of 1018 km of streams and 668 out of 786 km of shoreline from lakes were revealed to be accessible for the potential extraction of water. Considering smaller lakes without a connection to a stream, the latter is further reduced to around 331 km. When associated with the closest recharge locations, the remaining water sources appear within an average

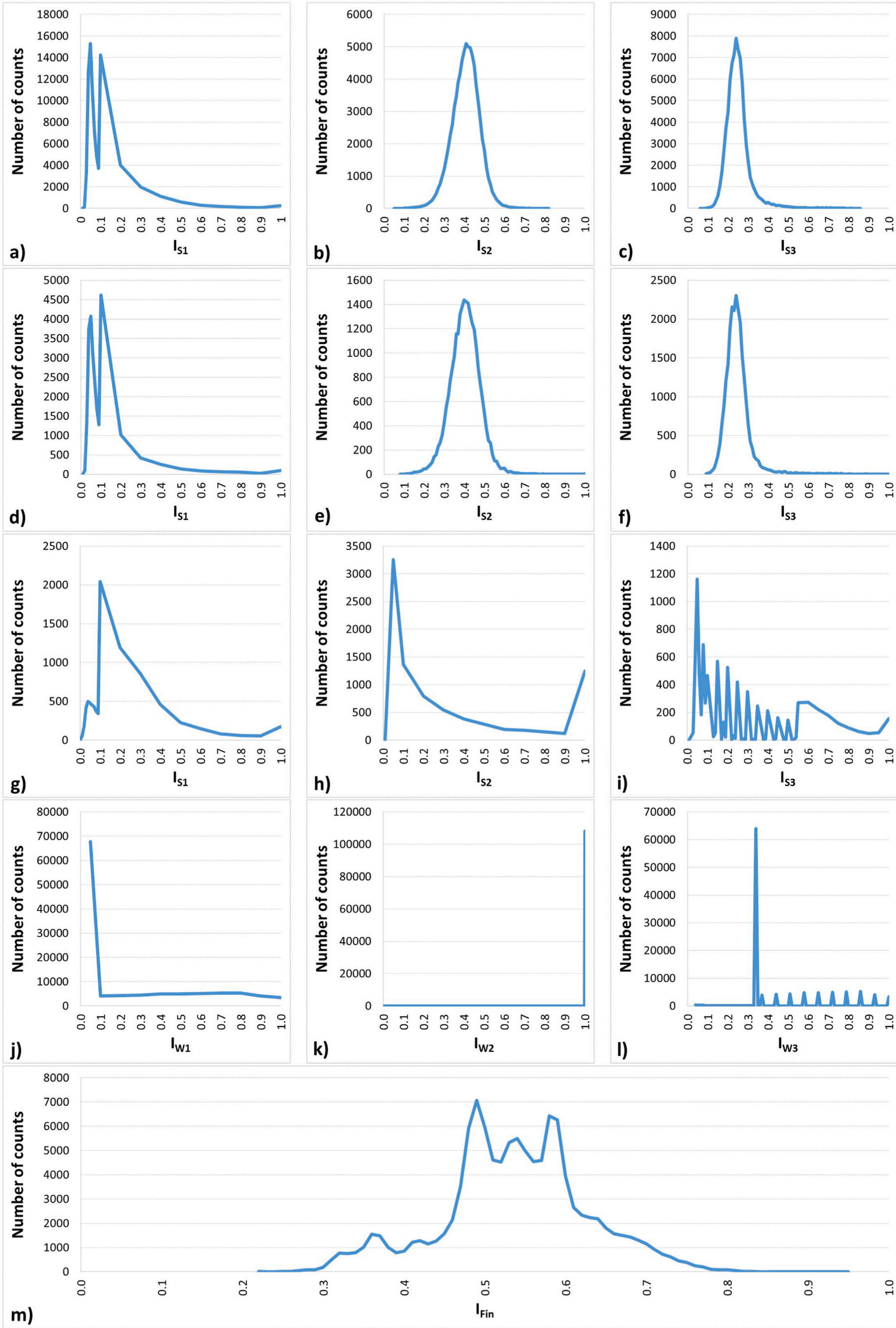

Fig. 5. Frequency distribution of the index values of natural (a–c), naturally adapted (d–f) and sinks enlarged through construction (g–i) as well as their associated water sources (j–l) and the total MAR suitability expressed by the index I_{Fin} (m).

distance of 1.8 km, equivalent to poor suitability ($W_1 = 0.05$) (Fig. 5 j). Aligned with that, almost 60 percent are located within 1 and 12 km, while only 3.13 percent lie within the most suitable distance of up to 100 m.

By contrast, the mean surplus volumes were identified to range widely from 7 to around 1,191,600 m^3 per day for the main river systems. Depending on the mostly topographically dominated dynamics of the surface water catchments, this equals between almost 0 and around 13 m^3 per second that are available during surplus water events (Figs. 2 and 3 c). Hence, 50 % of the potential extraction points each yield sufficient volumes (>1200 m^3), whereas around 10 % offer more than 10000 m^3. In relation to the associated sinks, around 95 % can be supplied with at least one complete filling per surplus day (I_{W2}) (Fig. 4 k). This potential is additionally increased by the average occurrence of surplus volumes that range from 73 to a maximum of 365 days per year, attributed to 18 % of all water sources. Despite that, the index I_{W3} represents a mixed pattern of both preceding indices and a medium average value of around 0.47.

In the next step, spatially limited hydrogeological data (91.24 %) were used, of which 2.18 % relate to unsuitable areas such as open cast mines and surface waters (Fig. 4 e). The other 39.21 % represent the absence of the first, upper aquifer complex, which is substituted by units of intermediate suitability ($I_{Hy} = 0.50$). Successful MAR benefits from proper aquifers such as complex 1.2. However, the accessibility of this unit for surface-induced recharge is lowered by a near-surface aquitard above it for 5.32 % of the data frame and it is therefore attributed an index of 0.75. The same accounts for the 29.21 % of the data that is covered by the mostly unconfined aquifer complex 1.1, located in potential discharge zones such as lowlands and glacial valleys. In combination with the remaining quarter (24.08 %) of the most suitable uncovered aquifer on elevated plateaus (1.2), the study area comprises high general suitability (~89.25 %) with partially excellent settings. Finally, all suitable land use types (48.07 %) were used to derive the feasibility (Fig. 4 d) of having an average 0.63 (I_{Fe}) for forest stands made up of more prominent coniferous and mixed forests of medium suitability. On the other hand, the agricultural feasibility's dependence on the average soil quality points (21.86) leads to a corresponding average suitability of 0.78. In the case of unused vegetation such as copses and heaths, this is accompanied by the highest suitability (1.00), but this only applies for less than 1 % of the study area. As a result, agricultural land and conifer forests retain the most dominant impact and sum up to the most prominent index of 0.50 (33 %). The latter is only undercut by around 5 % low-quality agricultural land and remains minor compared to the higher proportion of medium to good sites.

In combination, the overall assessment result (I_{Fin}) is assigned to every identified sink and reveals an index distribution that equals the standard distribution with only low counts for very low and very high values (Fig. 5 m). Most of the study area (around 75 %) is assigned a medium index (0.45–0.65) and therefore solid MAR potential.

4. Discussion

4.1. Method

With strict spatial and land use requirements, this approach allowed for intermediate surface water storage during the recharge process (Ulibarri et al., 2021) and enabled the identification of topographic sinks at various scales with further resolved and graduated landscape characteristics. The relatively flat landscape comprised challenges that could be resolved using the selected DEM (1 × 1 m) to detect even shallow and small agricultural sinks, and therefore discover the full potential of natural recharge locations. Nevertheless, possible inaccuracies caused by larger forest or seasonal agricultural vegetation could only be partially limited by preprocessing the DEM, meaning that the exact sink properties must be taken with caution.

Local slopes and thus the lower suitability of increased surface runoff of recharged water (e.g., Fuentes and Vervoort, 2020) were considered irrelevant for closed basins (LBGR, 2025) within a suggested regional slope (5 %) for successful groundwater recovery (Steinel et al., 2016; Rahman et al., 2012). Thus, the positive correlation of the pressure head with the vertical infiltration rate was considered more important (I_{S1}) and was mostly unaffected by declining effects of sediment compaction (Jódar-Abellán et al., 2017) due to the favorable anisotropy of the unsaturated zone (Ehrhardt et al., 2022) and the mostly shallow sink depth. In the same context, the effective use of the sink's volume (I_{S2}) was expected to represent the foundation's evenness and thus filling and infiltration dynamics, but can only deliver a rough indication with no clear implications depending on land use.

Therefore, the soil-related infiltration dynamics are considered crucial to introduce an exclusion-based minimum standard prior to the further categorization of effectiveness. The vegetation cover and the corresponding presence of macro pores can catalyze infiltration (Leimer et al., 2021) but remain unassessed and thrown into doubt regarding temporally saturated and therefore anoxic wilting conditions during recharge activities (e.g., Rabbel et al., 2018). Thus, the alongside evapotranspiration effects of vegetation were not considered as suggested (e.g., Alam et al., 2021) but is expected to be limited further during the winter's seasonal low. Instead, dynamic yield controlling factors such as cropping patterns, age distribution (Möhring and Rüping, 2008), and price margins (Hüttel et al., 2014) were substituted by an approach based on static soil quality to differentiate between relative agricultural yields and thus financial feasibility.

Accompanying, less suitable soil conditions were tolerated to enlarge the second set of recharge points in an unstructured way, contrasting the gradual extension of a slightly lowered depth to groundwater. In this process, sinks were primarily enlarged at the expense of reduced efficiency by first ignoring land use boundaries. They were only processed if partially extended to preserve their suitable character. During the artificial enlargement, the fragmentation of sink portions by streets or other linear land use restrictions was successfully counteracted (Fig. 4 f), but mostly failed to increase their maximum depth. Instead, deeper existing sink fractions were utilized within the restrictions of a fixed embankment foundation width, regardless of the necessary height, leading to a slight underestimation of their extent. However, this remains essential due to stability concerns that were set to limit the embankment and filling height (1.20 m; 1.00 m), which is why a comparably large number of sinks had to be downsized to fit these limitations. The limited boundary height does not always match the sink's maximum depth at its lowest point, and made it possible to utilize some areas on higher slopes (Alam et al., 2021). This included a precise replica (triangulated irregular network, TIN) of the present topography and individual embankment characteristics, which used to illustrate the aimed enlargement (S_1, S_2) and proved the concept by showing that the construction efficiency (R_C) was mostly sufficient. Nevertheless, one third revealed a negative construction balance ($R_C < 1.00$), primarily associated with sinks of smaller initial size or with a disproportionately long artificial boundary, which acted as a controlling factor for effectiveness.

To utilize these locations, the limitation of surface–groundwater interaction (Sophocleous, 2002) along close surface water sections (<50 m) (e.g., Fuentes and Vervoort, 2020) was considered insignificant (1.7 %) and further reduced by the prior avoidance of discharge areas where a certain proximity could favor ephemeral streams and groundwater-dependent ecosystems (e.g., Page et al., 2023).

Meanwhile, the available surplus volumes (I_{W2}) were revealed to be equal to or greater than the associated predominant small sink volumes ($R_V \geq 1$) in 95 % of cases, but to only represent a narrowed spectrum of capabilities due to the missing subdivision of R_V ratios greater than one. Correspondingly, one complete sink filling per day of surplus discharge can be received by most sinks regardless of their infiltration dynamics and is mostly efficient depending on the frequency of days when surplus volume is generated. However, the latter statement is still thrown into doubt by cases with surplus availability throughout the year. This can be compensated by a weighting factor that favors the distance-related index (I_{W1}), creating a more balanced result.

If redirected, this water can replenish hydrogeological units below, whereas the limited potential related to land and soil properties (Fig. 4 a, b, e) does not allow us to ignore units that are less suitable for supplying distributed localized recharge points. A restricted depth to groundwater and distance to water sources diminished the risk of recharge in discharge areas, but did not make it possible to determine the impact of recharge within near-surface aquitards and alternating layering.

4.2. Potential

The catchment's mostly rural setting comprises a great spatial potential of suitable land uses that favor the implementation of MAR at various scales. Although the maximum potential was only achieved in the case of unused, spatially insignificant land use types such as heathland and copses, most forested and agricultural land demonstrate sufficient relative feasibility such that the number of available recharge sites is not significantly lowered.

The potential of the hummocky landscape's almost continuous pattern of topographic sinks (Fig. 4 f) to comprehensively enhance the localized natural groundwater recharge (Vyse et al., 2020) could reduce ecological and financial losses. Although many of the assessed sinks are small, their wide range and quantity support the formation of local near-natural MAR clusters that can be used for intermediate storage and subsequent recharge. Recharge may thus be fostered on adaptable scales to fit the local needs.

If coupled with recharge-relevant soil property criteria, this selection is strongly reduced (21.88 %) by the presence of peat soils, groundwater-influenced hydromorphic states, high soil water contents, or shallow depths to groundwater (Table 1). This mainly affected locations near large surface water bodies (Fig. 4 b), which are associated with hydraulic discharge areas, whereas the remaining areas show potential that is mostly independent of land use and is medium to good in some cases. Variations are partly associated with differing data sets, categories, and scales that hinder the unconditional comparison of results but do not diminish the overall favorable impact, which may even support the efficient operation of smaller sinks through more frequent fillings.

Nevertheless, the extent of natural sinks remains partially restricted due to soil property criteria and was only slightly enhanced for the naturally enlarged sinks that comprise comparable index distributions and limitations (Fig. 4a–f), but did not require constructed measures. Nonetheless, the best utilization of the sinks' storage potential could only be achieved with partly artificially closed sinks that complement the ensemble of near-natural recharge basins. Although limited in quantity, sinks that are enlarged through construction hold great potential to artificially utilize the sinks' storage abilities by exceeding their natural extent.

The benefits of natural structures may be compromised by a fixed location being required, leading to the inflexible routing of water transport infrastructure. Unfortunately, this creates long distances ($\leq$12 km) for the preferred recharge on elevated plateaus, such that only half of the assessed locations can be considered realistic options (<1 km) (e.g., Maréchal et al., 2020). Luckily, the latter locations are mostly accompanied by a good return period of surplus discharge events and resulting surplus water volume (Fig. 4 l) to sufficiently supply almost all associated sinks. In this regard, extraction from these water bodies is not just an ecological burden, but may be sufficient with lower volumes to support a lengthened discharge phase of ephemeral streams by strengthening the stabilization of base flows (e.g., Kourakos et al., 2019). Being a crucial discharge component, especially during summer (Krause et al., 2007), MAR-controlled base flows could be considered an option to increase the climatic resilience of streams. Nevertheless, stream discharges within the catchment remain largely controlled by precipitation (Thomas et al., 2012) and are expected be subject to more frequent flooding events (Huang et al., 2015) on the other end of the spectrum of climatic uncertainties. MAR could therefore serve a dual use, also helping manage flood events (Maliva and Missimer, 2012) as part of a stormwater reuse strategy to retain more water within the catchment. The gained availability of water resources thus represents a cross-sectoral parameter that enables manifold developments in other sectors such as agriculture and forestry (Reyer et al., 2012) regarding climate change adaptation (e.g., shifted and prolonged vegetation period) (Bloch et al., 2015).

For around one quarter of the assessed area, this is possible through a relatively direct contribution to uncovered aquifers on elevated plateaus (1.2) that have a sufficient depth to groundwater, but are themselves shallow. The climatically challenged drought resilience of coupled ecological and surface water systems could therefore even be induced with lower recharge volumes. This potential is not limited to southern areas, but affects almost the whole study area, if the limited storage and transport capabilities of widely extended near-surface aquitards are pragmatically accepted. Although this is likely to induce a dampened, temporally shifted recharge signal (e.g., Racz et al., 2012), a long-term stabilization of the regional groundwater resources could be fostered through its effect on the main aquifer system below. The multi-factorial reasons for declining groundwater levels, which are important for human water supply (Wunsch et al., 2022), could thus be reduced by buffering groundwater extraction via MAR (e.g., Merz and Pekdeger, 2011). In this context, the study area's dense net of (partly) natural sinks and overall medium to good regional potential could foster the implementation of localized recharge measures as part of a regional transformation that can withstand upcoming climatic challenges and competing interests.

4.3. Limitations

Tailored to fit the requirements of surface infiltration, this approach cannot represent other MAR types, but could serve as an orientation when planning purely constructed infiltration measures and be extended to the overall data frame of the federal state of Brandenburg, or be transferred to other areas with similar Pleistocene characteristics.

Regarding land use, this can only be a temporary representation that fails to depict the fragmentation and individual prioritization of management zones and land ownerships. This concerns not just static soil properties, but also dynamic cropping patterns that are only considered in terms of their relative monetary feasibility without taking into account MAR-related benefits that could act as a buffer against soil drought (Alam et al., 2021) and thus yield losses (Schmitt et al., 2022), supporting stable absolute ecological and hydrological values. Hence, the presented results can serve as the basis for additional integrated surface–groundwater modeling that takes into account MAR-related surface water interactions such as extraction, a potentially increased base flow, and the transpiration losses that can be expected depending on land use, especially in permanently forested settings.

In this context, the water source's outlined ecological and mean threshold discharges remain uncertain and should only be considered as a guideline, whereas the assessed extraction volumes must be lowered by an unknown buffer factor to be derived by using this model. This especially applies to the roughly half of the assessed water bodies that have considerable distance-related importance ($I_{W1} > 0.05$) and will also have to undergo further on-site assessment, such as water quality checks, to maintain the study area's good groundwater quality (LfU, 2025).

In this regard, the infiltration basin's simple, cheap capabilities (Ross and Hasnain, 2018) to remove pollutants already represent the most conservative type of risk-limited recharge (Alam et al., 2021), especially for water with an unknown and variable composition (Page et al., 2018). The soil property assessment's main focus on the infiltration capacity favored high infiltration rates to avoid waterlogging and restricted flow (Bouwer, 2002), but neglected the concurrent risk of contamination.

Likewise, the hydrogeological setting was prioritized with regard to surface accessibility and conductivity, but should also be utilized to minimize water quality risks and associated costs (Vanderzalm et al., 2015). Although also variously present within forest stands (Riek et al., 2021), farmland in particular is at risk of pollution with nitrogen (Kersebaum et al., 2006) and a limited soil nitrate retention potential (Merz et al., 2009). Regardless of the nitrate threshold (50 g/m^3), it thus requires further on-site assessment prior to recharge. Nonetheless, the solids suspended in the source water are assumed to be the prior contaminant (e.g., Bari et al., 2021; Jokela et al., 2017) and could be handled by prior sediment retention (Steinel, 2011) within a set of neighboring sinks that take over separate or rotating retention and recharge functions (e.g., Masetti et al., 2016) to maintain sufficient infiltration rates (Pavelic et al., 2011). However, in a mostly remote setting, this would require more independent sources, such as renewable energy, to organize a power supply for pumps and technical equipment.

Simultaneously, the historic over-abundance of surface water led to the construction of a sometimes dense, and today mostly uncharted underground drainage network (Dietrich et al., 2019) that might hinder recharge activities (Merz and Pekdeger, 2011). Since this is found mainly in the lowlands to be discharged, our approach is likely to reduce the risk of interference, but that risk cannot be eliminated without direct on-site assessment.

Likewise, the remote analysis of topographic features remains uncertain in that the identified sinks may be potholes of glacial origin and thus feature less suitable soil properties (Gerke et al., 2010; van der Kamp and Hayashi, 2009) that may not have been represented by the assessed large-scale data. Hence, additional investigations, such as geophysical assessment (e.g., Parker et al., 2022; Behroozmand et al., 2019), should be applied to identify less permeable layers that lower the impact of surface-induced recharge (Sasidharan et al., 2021) on climatic impacts.

5. Conclusions

The potential of surface-induced MAR in the lower Spree catchment was assessed based on a comprehensive suitability index. This comprises setting criteria that determine whether land use units and their soil properties can be beneficial for unhindered infiltration and subsequent storage in the underground. To make use of their natural recharge capabilities, topographic sinks were identified within suitable areas and rated regarding their properties for intermediate surface water storage and recharge. The spatial limitations of natural structures that this revealed were compensated for by applying a less restrictive second set of criteria partially accompanied by constructed adaptations enabling near-natural recharge locations to be spatially enhanced. To utilize the identified potential, a water availability analysis was carried out to identify and evaluate the available surplus water volumes from extreme weather events in connection with the recharge sites. Finally, the accessibility of the shallow aquifer system was assessed and assigned a suitability index determined for each identified recharge site.

Each assessment result can therefore be used for the small-scale evaluation of specific sites and thus lower the barriers for the pre-evaluation of real MAR implementation. This not only demonstrated the potential of individual small-scale and near-natural MAR solutions but also showed the potential to strengthen water's resilience as a resource in the face of future climate changes within a regional context. This was illustrated by the numerous closely spaced topographic sinks and their capability to be utilized as a dense cluster of localized recharge points for intermediate storage and the consequent recharge of available surplus discharge water volumes. Although it clearly identifies unsuitable locations, the developed decision-making process also reveals a broad range of suitable sites, allowing us to make the necessary compromises that will favor an efficient, but widely distributed, implementation of the method to face the water-scarce setting. This was especially facilitated by the benefits of a wide spectrum of nature-based infiltration structures, but also accompanied by the challenges posed by non-constructed solutions.

Accordingly, our approach can be seen as a catalyst for simplified pre-planning and potential analysis in the context of climate adaptation using surface-induced MAR, forming a basis for focusing decision-making on further pilot investigations (Vanderzalm et al., 2015) and model-based validation. As this study was based on large-scale topographic features, it revealed a potential that extends far beyond the study area and can be found in many parts of the world with similar distinctive Pleistocene landscapes.

CRediT authorship contribution statement

Jan Stautzebach: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Jörg Steidl:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Christoph Merz:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Funding

This work was undertaken in the framework of the project Spree-Wasser:N and funded by the Federal Ministry of Education and Research (BMBF) [grant number 02WEE1633B].

Declaration of competing interest

The authors declare that they are not aware of any competing interests that may have influenced the reported work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2025.101549.

Data availability

Data are being prepared for the implementation in a freely accessible web-tool. Data can be made available on request.

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