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SUITABILITY MAPPING FOR SUBSURFACE FLOODWATER STORAGE SCHEMES

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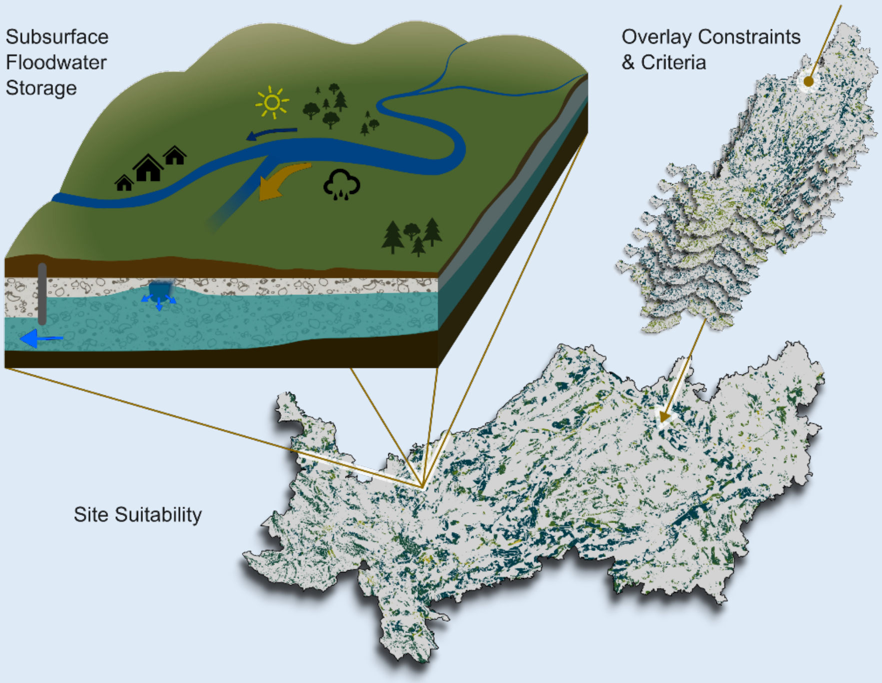
ABSTRACT



The hydrological conditions a changing climate imposes require updated measures to address extreme water events sustainably. These must evolve from isolated solutions, such as water retention basins, to holistic management strategies that consider at least two situations simultaneously, such as floods and droughts. One strategy for sustainable groundwater management is managed aquifer recharge (MAR), which copes with decreasing groundwater levels by a targeted recharge of aquifers. Using high water as a recharge water source (Flood-MAR) can additionally cover the aspect of flood protection, resulting in a multi-beneficial solution for the region. This study evaluated the site suitability for subsurface floodwater storage schemes, which must focus more on assessing the existing aquifer characteristics and the specific flood dynamics in nearby rivers compared to known MAR schemes. Potential sites for underground flood storage are characterized by decreasing groundwater levels and, thus, frequent water scarcity, combined with eminent risks of flooding by a nearby river.

Suitability, on the other hand, must take the aquifer, surface, and water source characteristics into account. In this study, we present a workflow for generating suitability maps for implementing subsurface floodwater storage systems with a geographic information system-based multi-criteria decision analysis (MCDA). The workflow was intentionally and exclusively based on publicly available data, was implemented in Python, and provided as open-source software. The resulting suitability maps spatially depict the feasibility of underground flood storage, and thus form the basis for the implementation planning of such projects. The approach was demonstrated for the administrative district of Swabia, Germany, where approximately 35% of the area was identified as suitable at varying levels. A sensitivity analysis of the assigned weights was applied to show the high robustness of the underlying data. The results highlighted the enormous potential of implementing such sustainable co-management schemes, which needs to be further concretized by on-site observations.

KEYWORDS

Flood and drought management, Managed aquifer recharge (MAR), Geographic information systems (GIS), GIS-based multi-criteria decision analysis (GIS-MCDA), Floodwater storage, Landscape water balance

1. INTRODUCTION

With global warming, an increasing number of people are affected by water scarcity and droughts. Increasing temperatures lead to higher amounts of water in the atmosphere, causing an increase in the intensity of precipitation events, often exceeding the infiltration capacity of the soil, and causing higher surface runoff. Therefore, the flood risk is projected to increase (38). Even in regions originally considered water-rich and secure in supply, such as Bavaria in Germany, longer dry periods, low water levels in rivers and lakes, and declining groundwater levels have been observed in recent years (10). For instance, in the administrative district of Swabia, southwestern Bavaria, the natural groundwater recharge from 2011 to 2020 was 18% below the mean value of 261 mm/a for the reference period 1971–2000 (10, 11).

Managed aquifer recharge (MAR) is a technology for sustainably controlling groundwater aquifers that has gained significant importance in the last 60 years (24). MAR refers to the targeted recharge of aquifers, which are then available for reclamation or the environment (23). Depending on the local circumstances and needs as well as the legal framework, recharged water can be obtained from various sources, such as river water, rainwater, stormwater, or desalinated seawater, to achieve benefits such as ensuring and improving the water supply by enhancing the groundwater quantity and quality. Although MAR implementation has increased at a rate of 5% per year since the 1960s, with groundwater withdrawals increasing even faster, there is still a lack of sufficient regulatory frameworks for its implementation (17, 24, 30).

An example of an emerging water management strategy combining flood risk reduction with drought preparedness is flood managed aquifer recharge (Flood-MAR), decisively shaped by the Californian Department of Water Resources. Using floodwater to conduct aquifer recharge keeps the precipitation in the region instead of transferring it quickly to the next main river or sea. Apart from flood and drought protection, it is beneficial to ecosystem services and helps adapt the regional water balance to climate change (45). The Flood-MAR Research and Data Development Plan, developed by a multidisciplinary research advisory committee in 2019, aims to support and expand the implementation of Flood-MAR projects at multiple scales (31). Apart from the coordination, funding, and feasibility analysis, various surface water sources and groundwater uses were considered. Site suitability factors, such as soil, crop, and aquifer suitability, should determine the site to be considered for recharge. Flood-MAR focuses on direct spreading methods, for example, on active agricultural or fallowed land (floodwater spreading; FWS) as well as dedicated recharge basins, but also directly via injection wells (45).

FWS is primarily used in arid regions of the Middle East and usually includes a dam to divert floodwater from the river and several interconnected siltation and infiltration basins (34). In 2014, 37 official projects were implemented across Iran (47). Underground taming of floods for irrigation (UTFI), another MAR specialization, uses infiltration wells in combination with ponds to store surplus surface water, for example in high flow situations, in dedicated groundwater recharge structures, thus preventing water deficits during the dry season (48). Owing to limited infiltration fluxes, this approach works best with seasonal floods of a longer duration (1). A pilot study site was located in the Gangetic Plain in India, where ten recharge wells were drilled into the base of a village pond, providing 26,000–62,000 m^3/year of recharged water for domestic and irrigation purposes. While the total amount of water stored seems to be negligible with regard to the overall flux in the river, the effect on water supply is significant: 75% of the infiltrated water is used to irrigate 9.6 hectares of wheat during the winter cropping season, and the remaining 25% is used to improve the flow conditions in the aquifer (49). A MAR derivative maintaining minimal land use is agricultural MAR (Ag-MAR), which aims to recharge groundwater by spreading excess water on agricultural lands (41).

Suitability maps with variably classified factors are effective tools for identifying MAR sites (e.g., 35, 50). Frequently, multi-criteria decision analysis (MCDA) is applied to consider multiple criteria and weigh them accordingly. Combining this with geographic information systems (GIS) helps organize, process, and analyze the results (50). Sallwey et al. (55) generated a database of over 60 studies published between 1998 and 2017, which used GIS-MCDA to select appropriate MAR sites. It was noted that there were only a few European studies and none from Germany (55). In 2015, the International Groundwater Resources Assessment Center (IGRAC) launched a MAR portal in collaboration with the INOWAS and DEMEAU projects as well as the IAH MAR Commission, providing a worldwide inventory of MAR schemes. The inventory includes 65 German MAR case studies clustered along the Rhine and Elbe rivers as well as in Berlin, but none in Bavaria (36).

The hydrological conditions imposed by a changing climate require co-management of floods and droughts. With the concept of smart storm water storage (Smart-SWS), the local water balance can be maintained even if heavy rainfall exceeds the infiltration capacity of the soil. Coping with opposing hydrological extremes is accomplished using decentralized, technically supported underground storage in existing aquifers, into which excess floodwater from a river is infiltrated. This technical implementation aims to store one or more heavy rainfall events or flood peaks and retain the stored floodwater for an extended period. The use of floodwater, infiltration with ditches, and temporal asymmetry bring new challenges compared with established MAR schemes. The high flow rates in the infiltration system required during a flood event to avoid flooding downstream regions can only be realized in aquifers with high hydraulic conductivity. Long storage times, on the other hand, are easier implemented if the groundwater flow velocities are low. As we focus on flood protection and drought prevention, the geotechnical regulation of groundwater flow in the storage area must be implemented. The infiltration system must be failsafe and work without an external energy supply, just by hydraulic gradients. This leads to the specific site characteristics required for Smart-SWS. Potential sites for underground flood storage are characterized by decreasing groundwater levels and, thus, frequent water scarcity combined with eminent risks of flooding by a nearby river. Suitability, on the other hand, must consider aquifer, surface, and water source characteristics.

This study presents a workflow for suitability maps for implementing subsurface floodwater storage systems with a GIS-based MCDA. The general workflow followed the suggestions of Rahman et al. (51)

for holistic MAR site selection: problem definition, constraint mapping, suitability mapping, and sensitivity analysis. For suitability mapping, a combination of the analytic hierarchy process (AHP) (54) and the weighted linear combination (WLC) (26) method was applied. The resulting suitability maps spatially depict the feasibility of underground flood storage, and thus form the basis for the implementation planning of such projects. This approach was demonstrated in this study for the administrative district of Swabia, Germany.

2. STUDY AREA

The administrative district of Swabia is located in southwest Bavaria, Germany (**Figure 1**) and was chosen because it encompasses a wide range of morphological, hydrological, and geological conditions. It covers an area of 9,992 km^2 with elevations between 390 m above sea level (asl) at the Danube river in the north of the study area and 2,649 m asl in the Allgäu Alps in the south. The region receives an annual precipitation of up to over 2,000 mm in the Alps, to a minimum of 650–750 mm along the Danube and

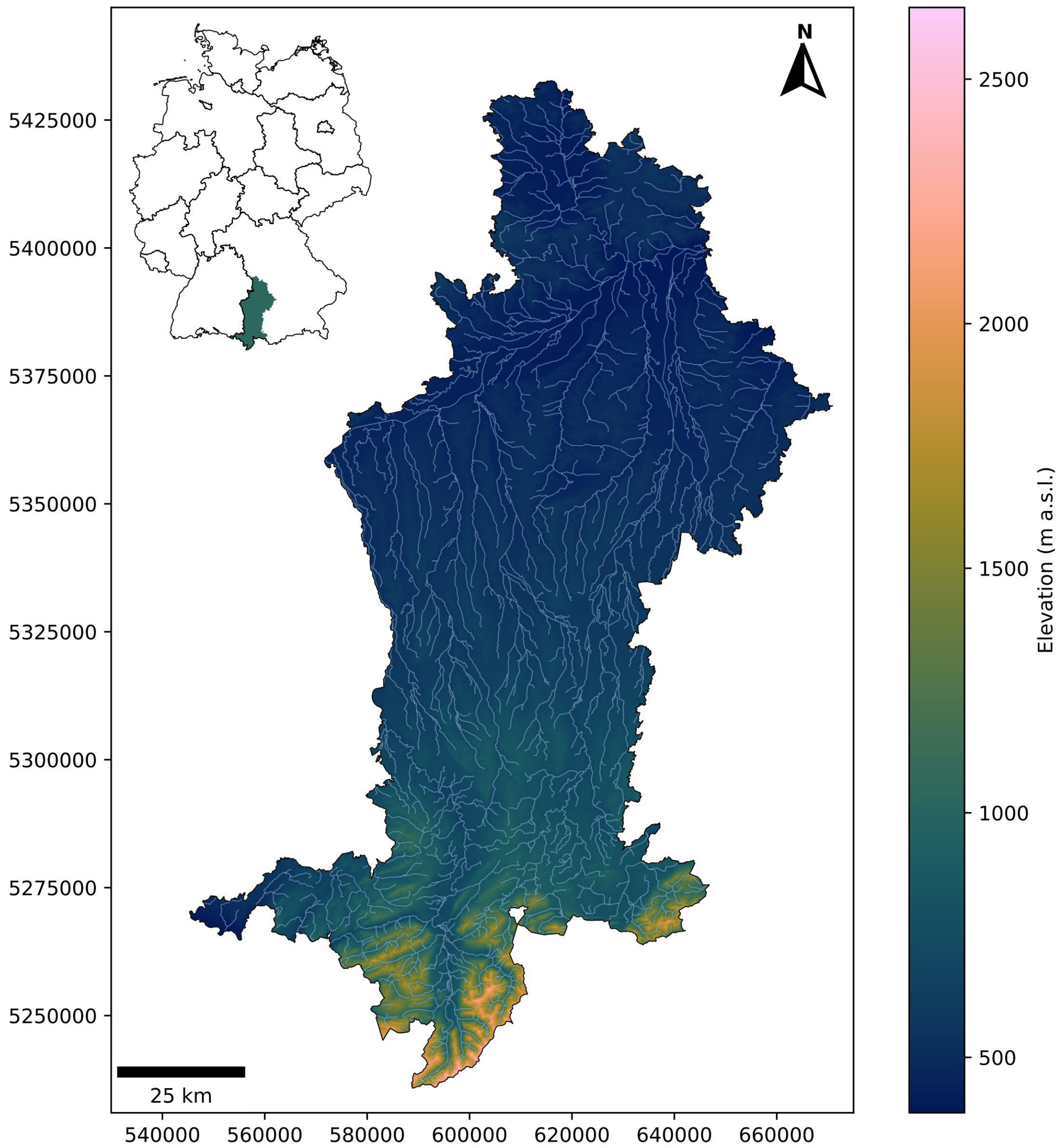


Figure 1: Study area: Swabia in Bavaria, Germany.

in the Nördlinger Ries (mean values from 1981–2010) (9). The annual mean temperature from 1951 to 2019 was 6.5°C in the southern part and 8.4°C in the northern part of the study area (13). The largest part of the Swabian river network (94%) belongs to the Danube catchment area, and the remaining 6% belongs to the Rhine catchment area in the southwest of Lake Constance. From north to south, the geological setting is characterized by the Swabian-Franconian Alb, including the shallow impact crater of the Nördlinger Ries. The Tertiary Hills shape the central part of Swabia. These sediments continue as a base layer for the quaternary deposits (sand and gravel from glacial meltwaters, end moraines, and moraines of the Alpine foothills) in the North Alpine Foreland Basin, and finally, the Prealps, and parts of the Alps, consisting mainly of shallow marine sediments, deep-sea deposits, and the Northern Limestone Alps (8). A geological map of the study area can be found in the **Supplementary Material** (available online).

3. METHODS

The GIS-based MCDA for identifying suitable sites was conducted as suggested by Rahman et al. (51) with (i) problem definition, (ii) constraint mapping, (iii) suitability mapping, and (iv) sensitivity analysis.

3.1. Problem Definition

Problem definition provides a framework for the MCDA process. In this study, the overall objective was adapted from the Smart-SWS concept: preventing floods without a flood retention dam or basin, if possible, and storing a significant amount of the flood wave in a nearby aquifer. Based on this, the technical specifications of such systems and a set of criteria for implementation were defined.

3.2. Data Collection

For this study, publicly available data were collected based on the criteria defined in **Table 1**. All raster and vector geospatial data were clipped or merged in the administrative district of Swabia. Drilling logs were provided as point data, which were then spatially extrapolated using Voronoi diagrams with Euclidean metric (4). Here, geological units from the digital geological map served as spatial constraints to avoid interpolation between different units.

Table 1: Data sources used for the MCDA.

Data	Source	License	Registration required for data use
Administrative boundaries	Eurostat – GISCO (28)	EU free re-use	No
River network	Copernicus Land Monitoring Service – EU-Hydro (29)	CDR 1159/2013	Yes
Digital elevation model (1 m)	Bavarian Surveying Administration – OpenData (6)	CC BY 4.0	No
Drillings	Bavarian State Office for the Environment – UmweltAtlas (16)	CC BY 4.0	No
Digital geological map (1:25,000)	Bavarian State Office for the Environment – UmweltAtlas (16)	CC BY 4.0	No
Land use (ALKIS)	Bavarian Surveying Administration – OpenData (6)	CC BY 4.0	No
Protected areas	Bavarian State Office for the Environment – UmweltAtlas (16)	CC BY 4.0	No
Gauging stations	Bavarian State Office for the Environment – UmweltAtlas & Hydrological Service & Flood Intelligence Service (14, 15, 16)	CC BY 4.0	No

In order to simplify the data acquisition for future analysis in Bavaria, Germany, all links to data used in this work are available here: https://gitlab.lrz.de/smart-sws/gis-mcda. This should be complemented by other federal states or countries to improve the transfer of the analysis.

3.3. Software

The workflow was implemented using the Python programming language[1], GeoPandas[2] (39), Shapely[3] (32), GDAL[4] (53), and SciPy[5] (33). The maps were visualized with Matplotlib[6] (19), using the scientific color maps by Crameri (22). The source code is available on GitLab: https://gitlab.lrz.de/smart-sws/gis-mcda.

3.4. Constraint Mapping

Non-feasible sites were sorted out in the process of constraint mapping by defining a threshold for decisive criteria. After assigning a 1 to alternatives that meet the threshold and a 0 otherwise, Boolean logic can be used to create a conjunctive map of feasible alternatives (if all criteria are 1) and non-feasible alternatives. The resulting constraint of the area defined the base map for further processing in the suitability assessment (51).

3.5. Suitability Mapping

Site suitability was calculated using the weighted linear combination (WLC) method (26) combined with the analytic hierarchy process (AHP) (54). This process comprises three main steps: (i) hierarchy identification, (ii) weight assignment with pairwise comparison, and (iii) synthesis of priorities (51).

3.5.1. Criteria Hierarchy

The starting point for identifying a criteria hierarchy was the review by Sallwey et al. (55), which harmonized 467 criteria from 63 studies that conducted GIS-MCDA for MAR suitability and clustered them into five main criteria groups: aquifer, surface, water quality, hydrometeorology, and management. Following the ideas of Rahman et al. (51), the relevant characteristics for Smart-SWS were selected and arranged in their own hierarchical tree.

3.5.2. Criteria Standardization

The criteria used in this study had significantly different scales. To remove scale bias in the resulting maps, all data were standardized to a range of [0, 1] with a perfect match resulting in a value of 1. The characteristics of the data were used to define transfer functions for criteria with continuous distributions (e.g., weighted linear combination for aquifer hydraulic conductivity). Stepwise functions with two to three steps were applied to the qualitative criteria (e.g., unsaturated zone thickness or land use).

3.5.3. Assignments of Weights

To assign weights to each hierarchy criterion, pairwise comparison was used following the method developed by Saaty (54) and first applied to MAR suitability analysis by Anane et al. (3). Here, the relative importance of each pair of criteria was set in the range of [1, 9] to obtain the reciprocal matrix $\boldsymbol{C}$. The vector of criterion weights $\boldsymbol{w}$ was then calculated with **Equation 1** where λ_{max} is the largest eigenvalue of $\boldsymbol{C}$.

$$\mathbf{C} = \boldsymbol{\lambda_{max}} \cdot \mathbf{w} \tag{1}$$

[1] Python programming language: version 3.10.4
[2] GeoPandas: version 0.12.2 (39)
[3] Shapely: version 2.0.1 (32)
[4] GDAL: version 3.7.2 (53)
[5] SciPy: version 1.8.0 (33)
[6] Matplotlib: version 3.5.2 (19)

The consistency ratio **CR,** to verify the weighting matrix, was computed using **Equation 2** with a random index **RI**, which depends on the number of criteria $\boldsymbol{n}$, tabulated in a table established by the Oak Ridge National Laboratory (3, 54). An inconsistency of up to 10% should be regarded as reasonable (54).

$$\mathbf{CR} = \frac{\lambda_{max} - n}{\mathbf{RI}(n-1)} \quad (2)$$

3.5.4. Combination of Criteria

Applying WLC as decision rule, the overall suitability index $\boldsymbol{S}$ of an alternative $\boldsymbol{a}$ at cell $\boldsymbol{i}$ can be obtained using **Equation 3,** where $\boldsymbol{w_k}$ is the normalized weight of criterion $\boldsymbol{k}$, and $\boldsymbol{v(a_{ik})}$ the standardized value of criterion $\boldsymbol{k}$ at cell $\boldsymbol{i}$ (43). $\boldsymbol{S}$, ranging from 0 to 1, was visualized in the resulting maps with a corresponding color map.

$$S(a_i) = \sum_{k=1}^{n} w_k \cdot v(a_{ik}) \quad (3)$$

3.6. Sensitivity Analysis

The robustness of the suitability analysis results was verified through a sensitivity analysis. From the methods outlined by Malczewski and Rinner (44) for GIS-MCDA models, a straightforward non-probabilistic approach was chosen for this study. The assigned weights for the criteria were varied using the one-at-a-time (OAT) method. We re-implemented the spatial AHP sensitivity analysis developed by Chen et al. (20) based on an ArcGIS tool in Python with a percentage change of 20. In addition, the sensitivity to the removal of one criterion at a time was analyzed.

The weight $\boldsymbol{w_k}$ of each criterion $\boldsymbol{k}$ was then either varied by a defined percentage change $\boldsymbol{pc}$ compared to the base level (**Eq. 4**):

$$w_{m*} = w_m + w_m \cdot pc \quad (4)$$

Or it was set to zero for removing the respective criterion ($\boldsymbol{w_{m*}}$= 0), whereby the other weights were adjusted so that they still met the requirement of adding up to 1 (**Eq. 5**), where $\boldsymbol{w_m}$ is the weight of the main changing criterion $\boldsymbol{m}$, and $\boldsymbol{w_{m*}}$ and $\boldsymbol{w_{k*}}$ are the adjusted weights of the criteria for the respective $\boldsymbol{pc}$.

$$w_{k*} = (1 - w_{m*}) \cdot \frac{w_k}{1 - w_m} \quad (5)$$

After varying each criterion weight by $\boldsymbol{pc}$ or removing it completely, the sensitivity results can be seen from the change in the superimposed suitability values. The change was quantified by calculating the mean absolute change in suitability per pixel for the two scenarios. The spatial changes can be illustrated by visualizing the deviation of the respective scenario from the base map.

4. RESULTS

4.1. Problem Definition

The combination of flood protection and drought prevention outlined in Smart-SWS is planned as an engineered infiltration ditch connecting the river to the aquifer, allowing it to infiltrate flood waves at elevated water levels by a natural hydraulic gradient (**Fig. 2**). Additional technical installations to reduce the outflow of groundwater will be implemented in the downstream part of the storage area. This could be a geotechnical measure, such as a sheet pile wall, which delays the discharge of infiltrated water by disconnecting the upper part of the aquifer, where storage is created, from the downstream aquifer, where natural groundwater flow continues undisturbed. One could imagine that the system reaches a certain distance above the bottom of the aquifer to allow natural flow below. At the top, the installation could reach up to 1–2 m below the surface; therefore, only minor interventions are expected after the

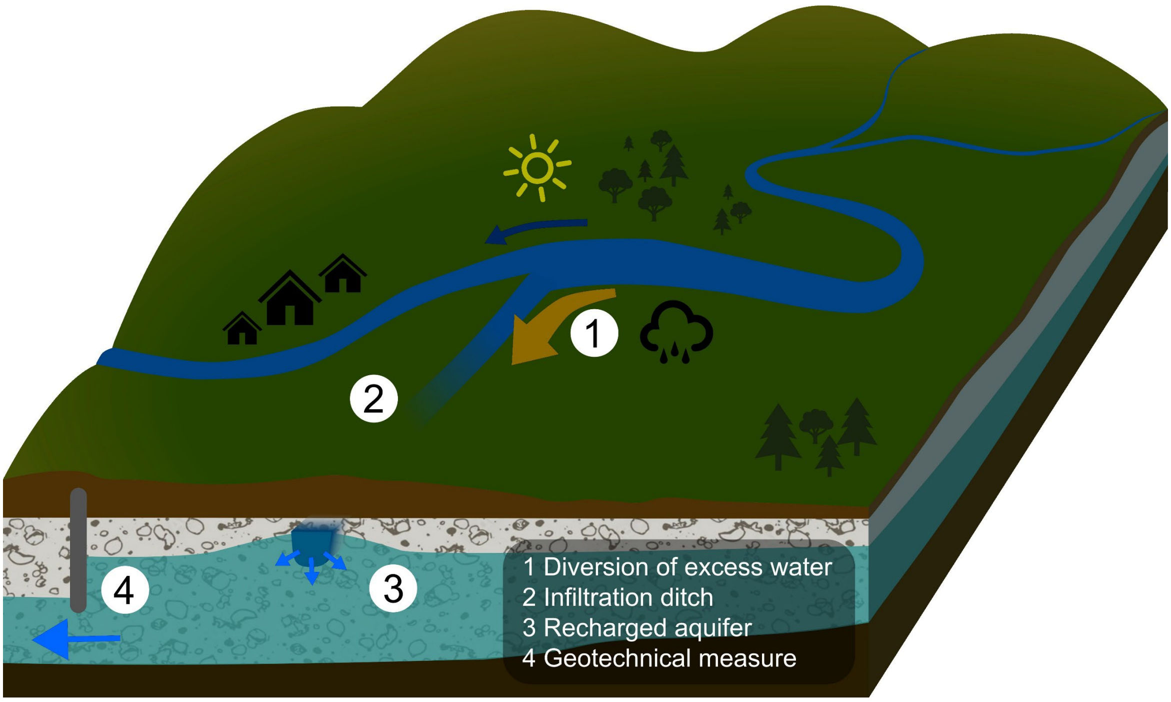


Figure 2: Concept scheme of Smart-SWS with diversion of excess water (1), infiltration ditch (2), recharged aquifer (3), and geotechnical measure, e. g., a sheet pile wall (4).

construction phase. Conditioning of the water to maintain an acceptable water quality of the infiltrated water is performed in the first part of the infiltration ditch and was not part of this study. To mitigate the potentially damaging peak of a stormwater wave in the stream, the Smart-SWS system must be able to absorb high volume rates for a very limited period of time. The design specifications used in this study were based on maximum volume rates of 5–10 m^3/s for up to 48 h and a total storage volume of approximately 400,000 m^3 with a storage time of up to six months. The design can be coupled with conventional flood retention basins to infiltrate even higher volumes of water and improve the overall retention in the case of more intense flood waves in larger streams. While infiltration is then extended over a longer time span to relax the requirements for the infiltrated volume flux, infiltration still occurs via infiltration ditches and not through the bottom of the retention basin. In this case, the additional outflow through the infiltration ditches helps to empty the basin earlier and/or reduce the size of the flood retention basin. This is favorable due to the reduced impact on agricultural use and the reduced environmental impact.

4.2. Definition of Criteria and Implementation in Thematic Maps

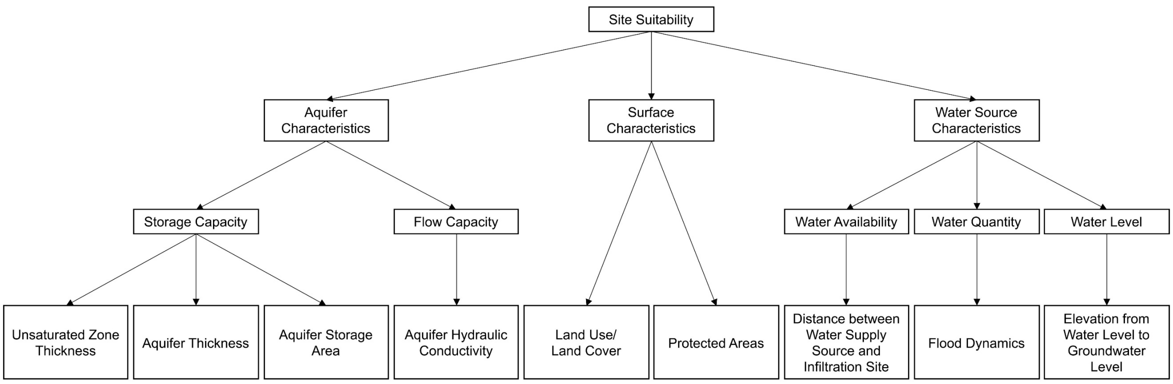


Figure 3: Criteria hierarchy for Smart-SWS.

Based on the technical requirements, the criteria shown in **Figure 3** were developed with partners from science, industry, administration, and legal counsel. The justification for each criterion is described below.

These criteria belong to three main groups: aquifer, surface, and water source characteristics. Aquifer characteristics were further subdivided into properties that control the storage volume and factors influencing the infiltration dynamics. The characteristics of the water source were subdivided into availability, quantity, and features that are controlled by the morphology of the storage system. The surface characteristics did not require subgroups.

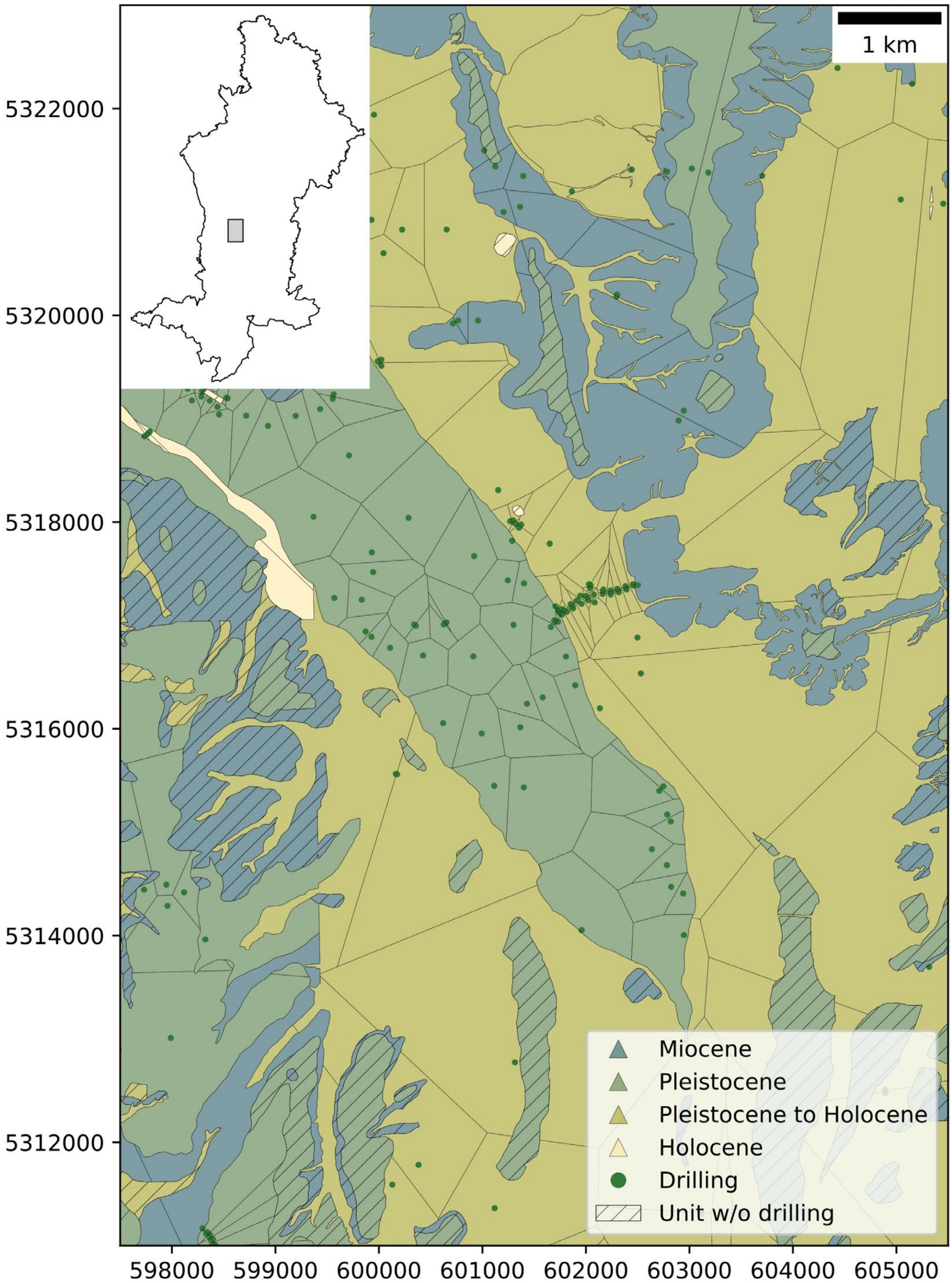


Figure 4: Spatial extrapolation of drilling logs using Voronoi diagrams with Euclidean metric.

4.2.1. Aquifer Characteristics

An ideal aquifer for Smart-SWS would be able to store at least one peak of a flood wave with a rise in groundwater level causing no damage to vegetation and infrastructure. The hydraulic conductivity is sufficient to distribute the infiltration wave from the infiltration ditches into the storage area between one infiltration event and the next. Well-defined aquifer boundaries with different petrographic conditions facilitate the delineation of the storage area, and funnel-shaped discharge reduces the required geotechnical measures. The scheme is well suited for unconfined aquifers but can also be applied to semi-confined aquifers if the hydraulic conditions are met.

Information on the aquifer can be derived from drilling logs that contain layer details. The drilling logs in the study area contained petrographic units and DIN classification of the sediments. The former can be directly linked to the labels in the digital geological map, so that they were used instead of the DIN classification to evaluate the different layers and the respective hydraulic conductivity classes (HCC). The definition of HCC helped to classify the petrographic labels designed in these logs: 1 for gravel, 2 for loose rock, 3 for sand, 4 for fine sand, 5 for silt, and 6 for clay, loam, stone, conglomerates, marl, or organic components. The top of the aquifer was defined as the first layer from the surface containing permeable material (HCC ≦3). This excluded the topsoil and cohesive sediments in the unsaturated zone in a few cases. The aquifer thickness now increased until a layer of lower hydraulic conductivity was reached (HCC>HCC-aquifer). Permeable layers were defined as aquifers if a minimum layer thickness of 2 m was reached or exceeded.

The quaternary and tertiary sediments of the shallow aquifers in the study area are characterized by (glacio-)fluvial or limnic deposition conditions and may contain lenses of materials with lower hydraulic conductivity. These lenses form in areas (or times) of low-flow conditions (lakes or oxbow lakes) (7, 46). This leads to a correlation between the thickness of these lenses and their spatial extent (e.g., 52). The occurrence of lenses was handled by separate logic in the evaluation. If a lens of lower permeable material was thin (<1 m), then the evaluation assumed a deposit of limited spatial extent, i.e., small compared to the potential storage area, and combined the aquifer parts above and below the lens. If the lens was thicker than the threshold, it was assumed to be hydraulically effective, and the separation from the upper aquifer layer was defined. If, according to the drilling log, the water level lay below the lens and in permeable material, or if the water table was not encountered during drilling, a different aquifer layer was expected, and only these different layers counted towards the aquifer thickness.

Point data provided by the drilling logs were spatially extrapolated using Voronoi diagrams with the Euclidian metric constrained to geological units (**Fig. 4**). Random tests showed that morphological features in the polygon can be neglected because the water table generally follows the morphology, the density of drilling logs is high (i.e., the polygons are small), and the geological units in this region are coupled to morphological features (i.e., gravel plains).

In Swabia, 21,235 of 30,965 publicly available drilling logs contained detailed layer information. Of these drillings, 14,100 met an aquifer with permeable materials (layer ≧2 m). In 2,008 boreholes, more than one aquifer separated by hydraulically effective lenses was recorded.

Unsaturated Zone Thickness

As groundwater is stored in an existing aquifer, the water table increases. To mitigate the impact on the surface, the unsaturated zone must be sufficiently thick to buffer this increase. Otherwise, high groundwater levels could damage buildings (40) or significantly affect surface vegetation (42). However, a high thickness of the unsaturated zone inflates the costs and effort of the geotechnical measure and increases the difficulty of reaching the groundwater level with the infiltration ditch. In contrast to MAR operations based on infiltration basins or wells (23), the unsaturated zone was not part of the infiltration pathway in the scheme considered in this study. Therefore, the hydraulic properties of the unsaturated zone and its ability to hold back pollutants are irrelevant in this context.

The thickness of the unsaturated zone was obtained from drilling data. An explicit water level was provided for groundwater wells, whereas for exploratory drillings, the depth at which the drilling first reached groundwater was usually logged. The dataset distinguished between no data available (NULL), groundwater had been reached (Yes), and groundwater had not been reached (No). In the latter case, and if no data were available, the depth of the drilling was taken as an indicator of the minimum thickness of the unsaturated zone, and the depth of the borehole determined its suitability depending on whether it was between the minimum and maximum values for the unsaturated zone. As described above, drilling logs were spatially extrapolated to geological units. If borehole data from a geological unit was unavailable, no assumptions could be made regarding the depth of the water table.

Out of the 30,965 drillings publicly available for Swabia, 16,346 logged that the groundwater level had been reached. The median recorded thickness of the unsaturated zone in quaternary and tertiary aquifers was 3.4 m, and the interquartile range (IQR) was 1.9–6.6 m. The maximum thickness was recorded with 109.3 m. The thickness was usually higher in tertiary aquifers.

Aquifer Thickness

The overall thickness of the aquifer was relevant in two aspects for Smart-SWS: the ratio between the saturated thickness at natural groundwater levels and the saturated thickness in a recharged state affects the flow conditions, which change more significantly at higher ratios, and the potential impacts on drought management, which are also more significant if the ratio is high. However, the high overall thickness of the aquifer increases the effort required to implement geotechnical measures to control the discharge from the storage system.

The thickness of an aquifer could also be derived from the drilling logs. The result of the aquifer definition logic (see above) was one or more identified aquifer layers with permeable materials. Because high thicknesses are desirable, the aquifer with the maximum thickness is decisive and was used for further suitability assessment. The median thickness of the aquifers (defined as permeable layers >2 m) was 5.9 m, with an IQR of 3.8–9.2 m. The highest values (up to 110 m) were recorded for tertiary aquifers. Spatial extrapolation was performed as previously described. If a spatial geological unit did not contain any drillings with geological information, the unit was passed to the subsequent evaluation without a value.

Aquifer Storage Area

The spatial extent of the storage area affects the storage event in two ways. First, the storage volume is defined as the specific storage coefficient multiplied by the maximum permissible rise of the groundwater table during storage in the aquifer multiplied by the area of the aquifer. Thus, a larger spatial extent is beneficial. Second, the spatial propagation of an infiltration wave determines acceptable infiltration rates and volumes. Again, a larger area is advantageous because it facilitates the spatial equilibration of water levels and allows longer infiltration ditches.

Data for this criterion were accessible through the digital geological map of Bavaria, which provided information about unconsolidated and solid rocks at ground level (first geological unit apart from the topsoil cover). For each geological unit, the area was available in shape files. Adjacent geological units with similar properties, i.e., units with the same stratigraphic series of rock formations, were combined. For Swabia, this resulted in 34,107 characteristic units merged from 83,172 original geological units. The area of these units varied from tiny fractions to Pleistocene units of over 580 km^2 (Mindelian river gravels).

Aquifer Hydraulic Conductivity

One of the most important prerequisites is that the aquifer is permeable and absorbs a high-volume flow. This capacity is determined by the geological stratification, with the hydraulic conductivity of the aquifer being the decisive factor.

The obvious choice for this type of data is hydrogeological maps, which ideally provide a qualitative or semi-quantitative description of the properties of the aquifer. However, these data are usually not available at the required spatial resolution or for the general public. Therefore, we used open data from drilling logs to assess the hydraulic conductivity of the aquifer. Because the conductivity of the strata was not given directly, petrographic classification was used for this criterion. For each aquifer identified with aquifer logic (see above), the hydraulic conductivity was evaluated, with the highest value being used for further suitability assessment.

Data on hydraulic conductivity were spatially extended via Voronoi diagrams inside geological units. The stratigraphic description from the geological map served as a proxy for units without drilling logs. However, in this case, the suitability metric based on the thickness of the individual layers making up the aquifer could not be applied. In Swabia, approximately 74% of the shallow aquifers are within quaternary sediments, followed by almost 20% in tertiary deposits. For 29.6% of the area, the assignment of hydraulic conductivity was based on the geological description alone.

4.2.2. Surface Characteristics

The ideal surface conditions for implementing Smart-SWS are outside precious ecosystems, groundwater protection zones, priority zones for mining, and high-quality land uses, but are easily accessible during construction and maintenance.

Land Use/ Land Cover

The implementation of the storage scheme is accompanied by construction activities for infiltration ditches and geotechnical measures, which, although minimally invasive, will lead to short-term restrictions on the access and use of land in the infiltration area. Extensively used open areas are less affected, compared to, e.g., high-quality tree cover or populated areas. Although the selection of technical measures will address the current use and the footprint of the implementation will be much smaller than, for instance, a flood retention dam and basin or an infiltration pond, the prevailing land use must be considered in the suitability analysis.

The official land use map for Bavaria (ALKIS; 5) distinguished between four main groups: settlement, traffic, vegetation, and water bodies. In Swabia, over 85% of the area fell into the vegetation group, leaving about 8% for settlements, 4.5% for traffic, and 2% for water bodies. The suitability of an area could be assessed in detail with further distinction between almost 140 different usage subtypes.

Protected Areas

Protected areas aim to conserve nature in the long term with their ecosystem services and cultural values (25). As a result of the European Natura 2000 network, endangered or typical habitats and species are preserved under the Birds and Habitats Directives[7] (27). The German Federal Nature Conservation Act defines the following nature protection areas (in descending order of restrictions): nature reserves, national parks, biosphere reserves, landscape protection areas, natural parks, and natural monuments. Furthermore, nature and landscape areas with special meaning as biotopes are protected (18). To protect water resources, drinking water and medical spring water protection areas have been designated. All the mentioned protected areas were added to this thematic map.

In Swabia, biotopes accounted for the largest share, with over 650 km^2 (6.6% of the study area), with most biotopes located in the Alps (3.7%), followed by the foreland (2.7%), and urban areas (0.2%). Water protection areas occupied approximately 410 km^2 (4.1%) of the study area.

4.2.3. Water Source Characteristics

An ideal water source for Smart-SWS is a stream or small river with exfiltrating conditions (i.e., a water level above the groundwater table), a highly dynamic response to precipitation in the catchment that carries a high risk of flooding, a well-defined flood volume, a discharge during flooding events that does not exceed the maximum fluxes in the infiltration ditches, and which is not too far away from a potential storage area.

[7] https://www.eea.europa.eu/themes/biodiversity/natura-2000/the-natura-2000-protected-areas-network/

Distance between Water Supply Source and Infiltration Site

The proposed combination of flood protection and drought prevention infiltrates river water into the nearby aquifers. As construction costs and significant interventions in the landscape are functions of the distance to the river, the distance between a river and the infiltration ditch must be limited.

The river network was taken directly from the shape files (29) and provided with a buffer to restrict the total area according to the mentioned constraints.

Flood Dynamics

The frequency and magnitude of flood events are criteria with technical and economic impact. Sites where floods occur infrequently are inherently less suitable for testing concepts and attempting to balance floods and droughts. The magnitude of a flood event determines the technical design of the infiltration system, and must match the storage capacity of the aquifer. In this study, we assumed that storing 10% of a flood wave (both magnitude and volume) will significantly impact the downstream development of the flooding event and aquifer recharge.

Flood dynamics were assessed by calculating the difference between a 100-year discharge (HQ100) or HQ (highest value of the total period), if HQ100 is unknown, and the mean discharge (MQ). This information was provided by the Hydrological Service and the Flood Information Service of Bavaria at 78 water level gauges in Swabia (14, 15). With the discharges at these gauges, conclusions can be drawn regarding the upstream and downstream suitability of the respective rivers. If the values at a gauge did not exceed the threshold, the metric for suitability was precise for upstream rivers, which were then identified as suitable. Likewise, the downstream part of the river can be unambiguously considered unsuitable if the discharge is above this threshold. The EU-Hydro data set includes the cumulative length, i.e., the total length of the river and all its tributaries leading to this point, for each river segment. The cumulative length was used as a proxy for the catchment area to interpolate the runoff. In the study area, there was an almost linear relationship between catchment area and cumulative length. Therefore, if the values at the gauge exceeded the threshold values and the gauge was the first gauge downstream from the source, a best-case approach was adopted, and the upstream discharge was approximated by linearly reducing the known discharge along the cumulative length of the river. At junctions, the discharge was diverted with respect to the proportions of the cumulative lengths of the respective tributaries. A similar approach was used to assess the suitability of an upstream gauge below and a downstream gauge above the threshold. Upstream gauges with known flood volumes functioned as fixed points so that the discharge at a main river, defined at junctions as a tributary with the highest cumulative length, was linearly reduced up to this point, including respective diverting at upstream junctions. Flood waves in large rivers and their tributaries are often out of phase and do not accumulate. However, it can be assumed that the flood wave propagates down to the confluence with the main river. Therefore, the known value of an upstream gauge at a tributary was linearly extrapolated to the main junction with respect to the cumulative length. Suitability was transferred to buffer areas next to the rivers (see above). A higher value takes precedence over overlapping buffers.

There were 78 gauges in the study area, and 13 rivers had more than one gauge. The median of the river chainage at the gauges was 14.4 km (IQR = 2.1–72.0 km), and the median of the upstream catchment at the gauges was 126.7 km^2 (IQR = 48.4–509.1 km^2).

Elevation from Water Level to Groundwater Level

The storage design relies on a natural hydraulic gradient to infiltrate flood waves into the aquifer. Therefore, the elevation difference in the water tables was decisive. Ideally, the groundwater level should be below the river level at all times. A minimum requirement is that the water level in the river is above the groundwater level during flood events. This requirement must be met at the actual infiltration ditch, which can be further away and downstream from the point where the water is exfiltrated from the river.

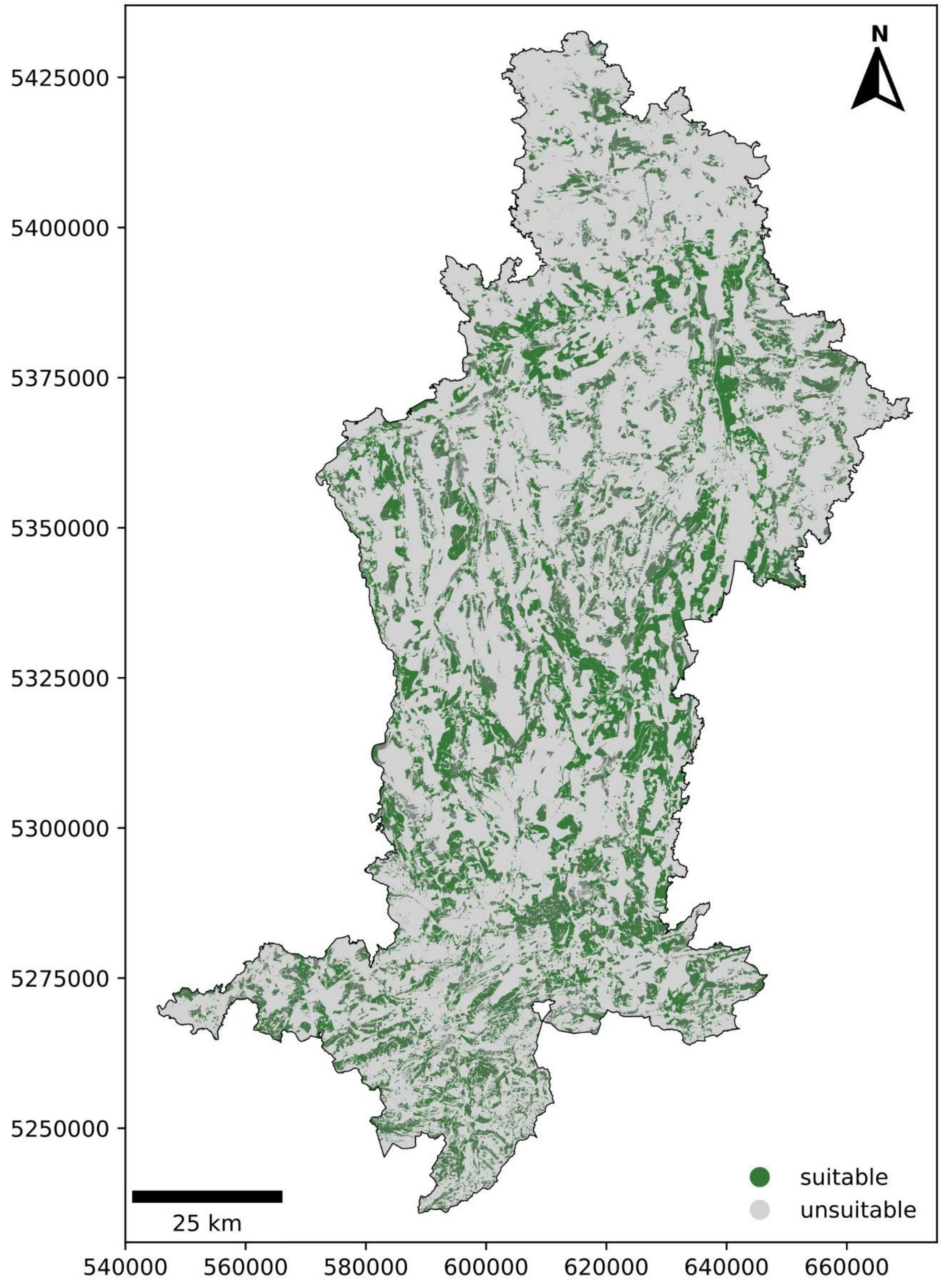


Figure 5: Constraint map resulting from overlaying the six identified constraint criteria.

The river elevation was obtained from a digital elevation model (DEM) with a resolution of 1 m. The groundwater table was spatially extrapolated using Voronoi diagrams, similar to the unsaturated zone thickness criterion. For each polygon, a buffer of 1 km was applied to obtain the maximum applicable water level in the river, which was then compared with the groundwater level within the polygon. This implements the concept of directing the river water into a downstream aquifer.

In our study area in the south of Germany, rivers in the northern part were more likely to receive water, i.e., the groundwater level is above the river water level. Rivers and streams flowing on glacial deposits in the southern part of the study area often infiltrated into the groundwater aquifer.

Table 2: Constraint criteria with their constraints to identify unsuitable sites.	
Criterion	**Constraint**
Unsaturated zone thickness	<2 m or >20 m
Aquifer storage area	<30,000 m^2
Aquifer hydraulic conductivity	Neither gravel, loose rock or sand
Land use / Land cover	Settlement[1], traffic (except paths) or water body
Protected areas	National parks, drinking water protection areas
Distance between water supply source and infiltration site	>1 km

[1]*Residential area, industrial and commercial area, slag heap, open-cast mine, pit, quarry, area of special functional character, cemetery. Excluded: Area of mixed use, sports, leisure and recreation area.*

4.3. Constraint Mapping

Table 2 lists the six constraint criteria used to exclude unsuitable sites and their corresponding thresholds. After applying all the constraints in the district of Swabia, approximately 34.8% of the area was left for further suitability assessment (**Figure 5**). The main restrictions in the study area were hydraulic conductivity (excluding 29.0%), distance to the river (excluding 23.4%), and unsaturated zone thickness (excluding 20.0%). Land usage, protection zones, and available storage areas were responsible for only a few exclusions. The study area north of the Danube River seemed less suitable than the area in the south. This was mainly caused by the geological setting, which was dominated by limestones, sandstones, and claystones of the Jurassic and Ries impact craters. All were covered with a thin layer of alluvial sediments. Although the limestones of the Upper Jurassic showed karst features and very high hydraulic conductivities, this aquifer was confined in the study area, and therefore inaccessible to Smart-SWS. The river network is denser close to the Alps with many small streams. This resulted in a smaller distance between the acceptable areas.

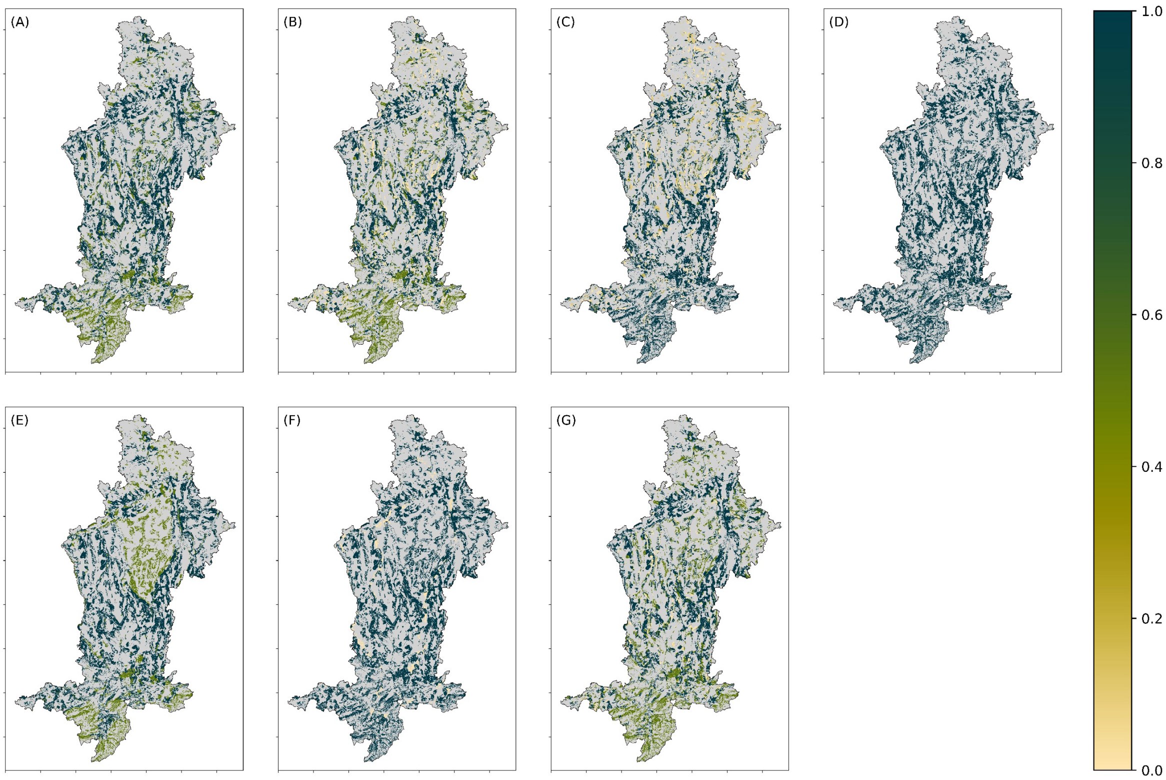


Figure 6: Suitability maps resulting from applying the respective suitability function based on the constraint mask. Color map ranging from 0.0 (least suitable) to 1.0 (highest suitable). **A**: Unsaturated zone thickness, **B**: aquifer thickness, **C**: aquifer hydraulic conductivity, **D**: land use, **E**: protected areas, **F**: flood dynamics, **G**: elevation from water level to groundwater level.

4.4. Suitability Mapping

Table 3 specifies the seven selected suitability criteria, with their respective suitability functions ranging from 0 to 1. Stepwise functions were generally applied to these criteria because no linear or other correlations occur. For the aquifer hydraulic conductivity, a weighted linear combination was used.

Table 3: Suitability criteria with their suitability assignment (constraint criteria from Table 2 are not repeated here).

Criterion	Suitability	
Unsaturated zone thickness	1:	2–20 m
	0.5:	If no drilling data in geological unit available
Aquifer thickness	1:	2–20 m
	0.5:	If no drilling data in geological unit available
	0:	< 2 m or > 20 m
Aquifer hydraulic conductivity	*If drilling data in geological unit is available:*	
	0–1:	Fraction of gravel * 1 + fraction of loose rock * 0.5 + fraction of sand * 0.1 + fraction of other components * 0 (for completeness)
	If no drilling data in geological unit is available:	
	1:	Stratigraphic unit ∈ Pleistocene, Pleistocene to Holocene, Pliocene to Pleistocene, or Holocene
	0:	Else
Land use / land cover	1:	Area ∈ mixed use, sports, leisure, and recreation area; paths; agriculture, forest, woodland, heathland, vegetationless area
	0.5:	Bog
	0:	Swamp
Protected areas	1:	None
	0.5:	Nature reserves, biosphere reserves, Natura2000 sites (habitats and birds directive), landscape protection areas, natural parks, biotopes, medicinal spring protection areas
Flood dynamics	1:	Q (= HQ – MQ) ≤ 100 m^3/s
	0:	Q (= HQ – MQ) > 100 m^3/s
Elevation from water level to groundwater level	1:	Water level ≥ groundwater level
	0.5:	If no groundwater depth in geological unit available
	0:	Water level < groundwater level

Figure 6 shows the suitability maps for each criterion resulting from applying the defined suitability functions. The individual maps are included in the **Supplementary Material** (available online). The mean suitability value for the unsaturated zone thickness criterion was 0.81, with a standard deviation (SD) of 0.24. The aquifer thickness criterion's mean suitability value was 0.64 (SD = 0.38). Both criteria showed a fairly homogeneous spatial distribution, except in the southern part of the Alps. As almost no drilling logs were available in this area, the suitability value across the region was 0.5, indicating that no clear statement can be made. For the hydraulic conductivity criterion, a mean suitability value of 0.63 and a standard deviation of 0.46 was recorded. The well-permeable glaciofluvial quaternary deposits in gravel plains and Holocene fluvial deposits in riverbeds are generally well suited. Therefore, clusters with high suitability could be observed along the rivers and streams in the southern part of the study area. The highest mean suitability value was observed for the land use criterion (1.00, SD = 0.03). This makes sense because only bogs and swamps reduce the suitability value of an area, covering only 0.13% of the study area, making their effect barely noticeable. The mean suitability value for the protected areas criterion was 0.74 (SD = 0.25). While most of the area was not protected (suitability = 1.0), the "Augsburg Westliche Wälder" nature park (1,224 km^2), relatively centrally in Swabia, and the protected areas in the Alps (mainly Natura2000, nature reserves, nature parks, landscape conservation areas, and biotopes) stood out on the map. For the flood dynamics criterion, a mean suitability value of 0.94 (SD = 0.24) with

a relatively homogeneous spatial distribution could be seen. The elevation from the water level to the groundwater level criterion showed a mean suitability value of 0.73 with SD = 0.31. In the southern part, the lack of drilling data could also be observed here in the suitability of 0.5.

Finally, the seven suitability criteria were ranked to obtain a pairwise comparison matrix $\boldsymbol{C}$ (**Table 4**). The weight vector was then calculated using the largest eigenvalue $\boldsymbol{\lambda_{max}} = \mathbf{7.196}$. With a consistency ratio of $\boldsymbol{CR} = \mathbf{0.025}$, calculated using the random index $\boldsymbol{RI} = \mathbf{1.32}$ for $\boldsymbol{n} = \mathbf{7}$ (54), the inconsistency could be considered acceptable.

Table 4: Pairwise comparison matrix defining the relative importance of the seven selected suitability criteria.

	A	B	C	D	E	F	G	Weight
A	1	2	1/3	4	3	1/4	1/2	0.104
B	1/2	1	1/4	3	2	1/5	1/3	0.068
C	3	4	1	6	5	1/2	2	0.240
D	1/4	1/3	1/6	1	1/2	1/7	1/5	0.031
E	1/3	1/2	1/5	2	1	1/6	1/4	0.045
F	4	5	2	7	6	1	3	0.354
G	2	3	1/2	5	4	1/3	1	0.159

A: Unsaturated zone thickness, B: Aquifer thickness, C: Aquifer hydraulic conductivity, D: Land use, E: Protected areas, F: Flood dynamics, G: Elevation from water level to groundwater level.

Figure 7 displays the resulting suitability map for Swabia. Of the areas remaining after applying the constraint criteria, nearly 70% were highly suitable, with suitability values greater than 0.8. Approximately 2.5% of the suitable areas had suitability values below 0.5.

4.5. Sensitivity Analysis

Table 5 summarizes the changes in suitability values, expressed as the mean absolute change in suitability per pixel for a relative change in the weight of every single criterion by 20%, as well as for the removal of one criterion at a time. In this study, we used a continuous distribution of the final suitability values without defining thresholds and ranges for the overall suitability (e.g., highly suitable range (2)) so that a linear response function was observed.

Table 5: Sensitivity analysis results from varying the weight of one criterion at a time or completely removing it.

	Initial Weight	Mean Absolute Change per Pixel		Normalized Change per Pixel	
		$\boldsymbol{w_m} \pm \mathbf{20\%}$	$\boldsymbol{w_m} = \mathbf{0}$	$\boldsymbol{w_m} \pm \mathbf{20\%}$	$\boldsymbol{w_m} = \mathbf{0}$
Unsaturated zone thickness	0.104	0.004	0.021	0.041	0.205
Aquifer thickness	0.068	0.003	0.017	0.051	0.255
Aquifer hydraulic conductivity	0.240	0.015	0.073	0.061	0.305
Land use / land cover	0.031	0.001	0.005	0.032	0.162
Protected areas	0.045	0.002	0.008	0.038	0.188
Flood dynamics	0.354	0.017	0.087	0.049	0.246
Elevation from water level to groundwater level	0.159	0.008	0.039	0.049	0.243

The highest sensitivity was observed for the flood dynamics criterion, followed by the aquifer hydraulic conductivity. Land use/land cover and protected areas had the lowest sensitivity. Overall, the sensitivity ranking followed the weight ranking. The normalized response function (absolute change divided by initial weight) showed subtle differences. There was no linear relationship between the normalized response and initial weight, which was expected based on the mean absolute changes. Aquifer hydraulic conductivity had the highest relative effect, followed by aquifer thickness, flood dynamics, and elevation from the water level to the groundwater level, which had similar effects.

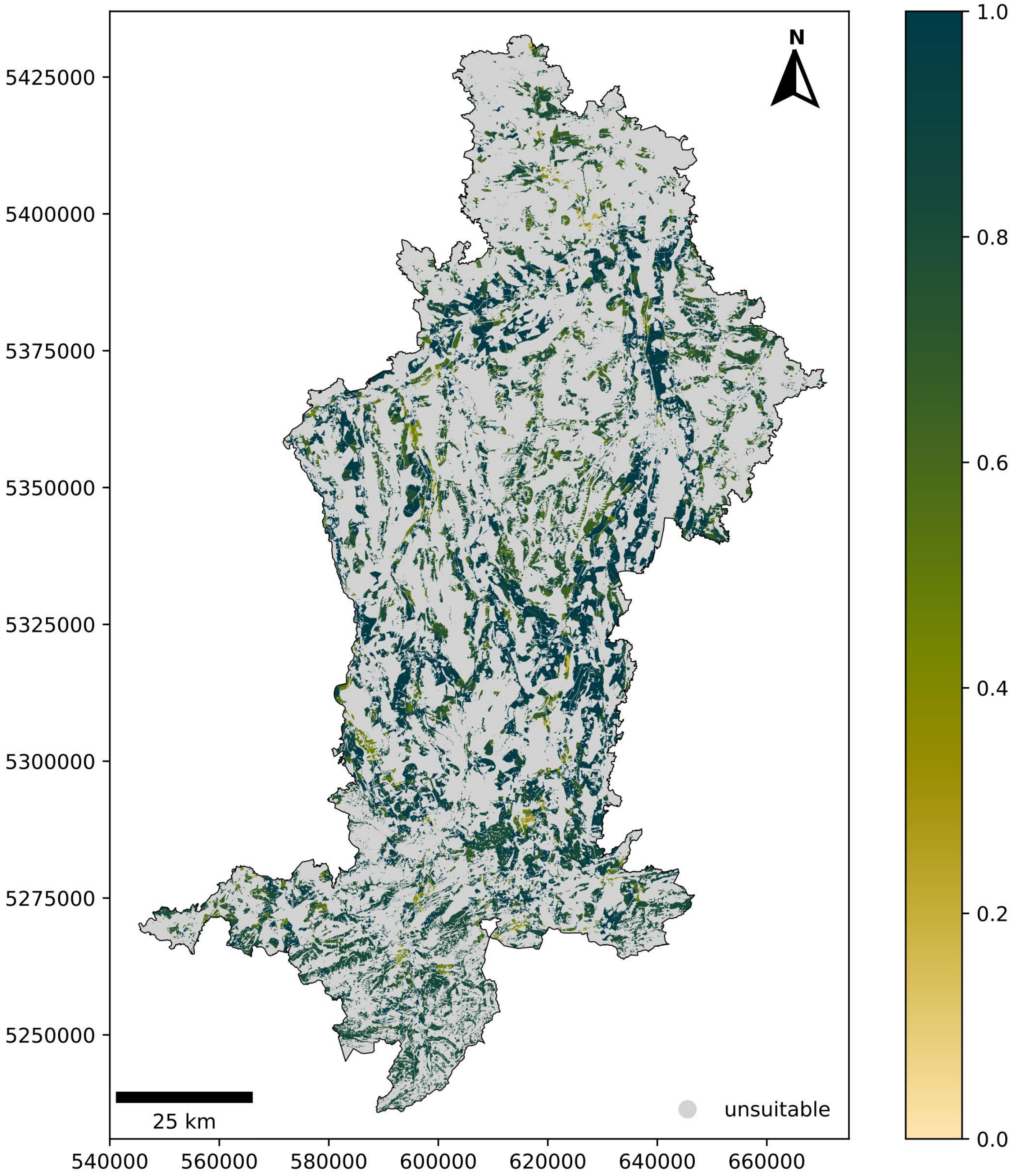


Figure 7: Suitability map resulting from a weighted overlay of the seven suitability criteria on the constraint mask. Color map ranging from 0.0 (least suitable) to 1.0 (highest suitable).

The mean absolute change in suitability per pixel captures the sensitivity to changes in the parameter weights. However, in many cases, it is desirable to elucidate the spatial patterns of sensitivity. Therefore, we provided the spatial distribution of changes by plotting the difference in suitability between the base map and the respective scenario in **Figure 8** for the removal of one criterion at a time. Positive values indicate an increase in suitability owing to weight changes. The individual maps for each criterion are included in the **Supplementary Material**, which is available online.

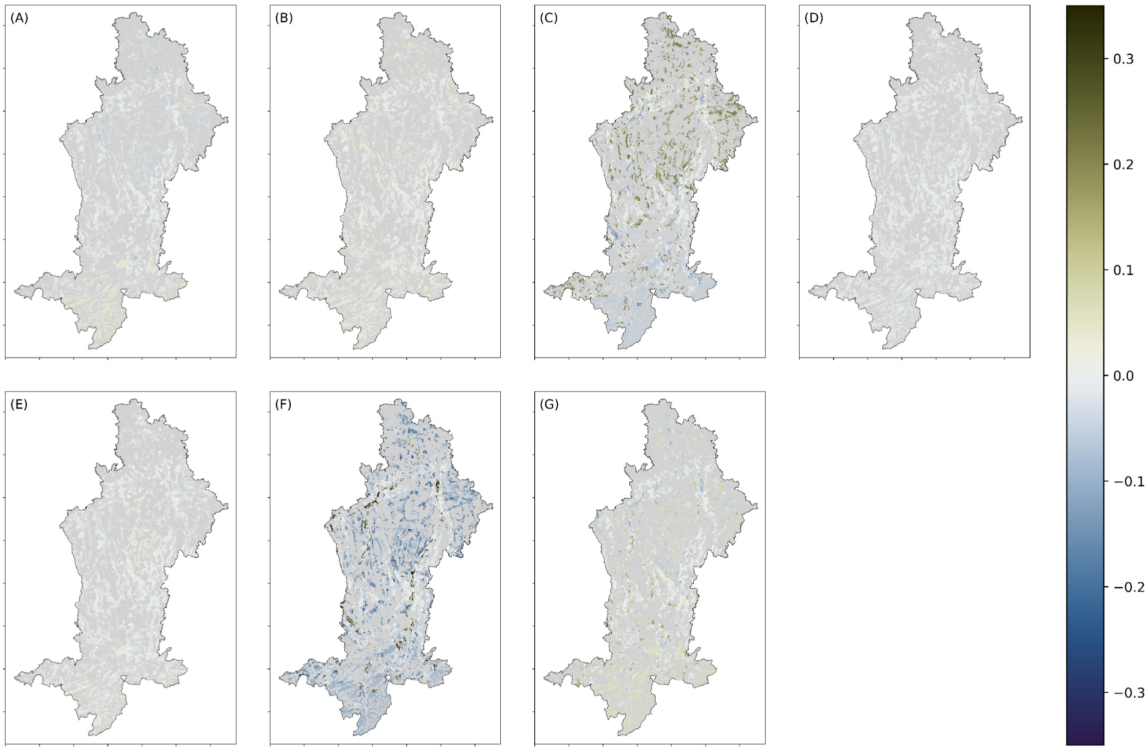


Figure 8: Difference maps between the base map and sensitivity analysis scenario excluding the respective criterion. Color map ranging from + 0.35 (higher suitable compared to base) to - 0.35 (lower suitable compared to base). Each of the above maps can be viewed individually in the **Supplementary Material**, which is available online. **A**: Unsaturated zone thickness, **B**: aquifer thickness, **C**: aquifer hydraulic conductivity, **D**: land use, **E**: protected areas, **F**: flood dynamics, **G**: elevation from water level to groundwater level.

5. DISCUSSION

5.1. Data Availability

Only a few studies conducting GIS-based MCDA for MAR broached the issue of data availability, even though it is crucial for selecting criteria (55). In this study, the criteria were selected independently of the data availability. In the developed workflow, we explicitly used only data that were open to the public and could be downloaded as vector or raster files with all attributes without fees or usage restrictions. Occasionally, data were available in interactive web mapping applications, such as discharge at gauges. If no other data sources were available, these data could be selected using Python scripts.

For some criteria, our open data policy led to workarounds, such as aquifer hydraulic conductivity or the groundwater table. Here, hydrogeological maps are an obvious choice for this type of information. However, for our study site, hydrogeological maps for the general public were available only at a maximum resolution of 1:250,000, which is insufficient for this type of MCDA.

While data availability for the study site seemed exceptionally good, the situation in other federal states of Germany and other countries is or might be worse. This can limit the spatial extent of the assessment if not all data is available for the whole region, but, for example, only on a county level, or it can reduce the level of detail if criteria are omitted or approximated. As a starting point, we provided our data sources on GitLab and welcome additions.

5.2. Data Quality and Sensitivity

Based on our sensitivity analysis, the workflow appeared to be relatively robust to the uncertainty of the underlying data. Even the removal of one criterion changed the mean suitability by a maximum of 8.7 percentage points. Data quality was excellent for land use / land cover (shape files), digital elevation model (1 m raster), and protected areas (shape files). To check the effects of the resolution of the DEM, the only raster dataset, we performed the MCDA on 1 m and 5 m elevation maps. The MCDA with a 5 m DEM resulted in slightly (2%) fewer areas being classified as suitable. This was primarily due to the averaging of the river heights projected onto the DEM. Tests with the elevation data of the segments in EU-Hydro derived from a 30 m DEM have shown that a resolution of more than 5 m is unreliable, as averaging effects compensate for smaller valleys with steeper slopes. The data quality for aquifer thickness and unsaturated zone thickness directly depended on the drilling log quality and quantity, where large gaps in rural areas away from the main traffic routes emerged. Derived data, such as elevation from water level to groundwater level and the indirectly determined aquifer hydraulic conductivity, would be the first data requiring on-site confirmation. The data quality of the flood dynamics at the gauging stations, which had the greatest impact on suitability (see **Table 5**), was generally high because these data were used for flood protection plans and were carefully validated. Here, the problem is sometimes the insufficient density of gauging stations, which can be easily improved by local measurements. Flood dynamics is also one of the parameters likely to change due to climate change and any upstream measures (renaturation, retention basins, land use), and should therefore be considered volatile.

One of the most important data sources for this MCDA was drilling logs, as four of the nine criteria process these data. Therefore, the quality of logs and their spatial distribution were significant sources of uncertainty. Of the 30,965 publicly accessible borehole logs in Swabia, 68.6% contained detailed layer specifications. Information on whether groundwater was encountered was provided by 62.3% of logs. Geological units containing drilling logs were spatially extrapolated using Voronoi diagrams, resulting in 54,739 polygons covering 70% of the study area. Spatial uncertainty could be seen from the area of these polygons, with a median of 0.076 km^2 and an IQR of 0.018 to 0.281 km^2. Geological units without drillings had a median area of 0.015 km^2 (IQR = 0.005–0.052 km^2). The spatial uncertainty is highest for large units without drilling, followed by large Voronoi cells. There is an increasing number of geothermal drillings for ground sources and groundwater heat pumps, which could provide a better understanding of the spatial variability of the subsurface. However, almost all of these installations (>99.5% for the study area) were in settlements and industrial areas, which were excluded by our constraint criteria and were not applicable to this analysis. If, for geological units without any drilling, no other indication of suitability was available, a suitability of 0.5 was ascribed. This does not provide information about qualitative suitability, but rather about the lack of data. The results of the site selection process can be improved using spatially well-resolved and high-quality drilling data.

The uncertainties originating from drilling logs and flood dynamics at gauging stations have different origins. Drilling logs may suffer from poor geological description. This generally affects a rather small area around the drilling site. Uncertainty in flood dynamics usually results from a lack of data, and normally affects larger stretches of the river. A comparison of the uncertainties of drilling and gauge data revealed that uncertainties in drilling logs can have a more significant impact on the final suitability map, as two constraint criteria (unsaturated zone thickness and aquifer hydraulic conductivity) are dependent on these data. A high density of logs can partially compensate for this uncertainty, as suitability values are assigned to individual Voronoi cells, which in turn can be validated by surrounding polygons. In the case of river data, uncertain suitability values are extrapolated to a large area, which was also reflected by the sensitivity analysis results; however, sites are not excluded completely.

5.3. Validation of the Aquifer Logic

The logic for deriving the vertical extent of the relevant aquifers from drilling logs was tested against a manual hydrogeological assessment based on the soil classification (37), petrographic description, and lithostratigraphic setting of all 368 boreholes with high-quality drilling logs (reference profiles) in the study area. Manual assessment identified the same aquifer strata as the lens logic for 343 drilling logs (93.2%). For 2.5% of the drilling logs, the lens logic had a false negative result, and for 4.3% of the drilling logs, the logic had a false positive result. Therefore, this logic was deemed suitable for further assessment.

A comparison of the results of our assessment with the hydrogeological map for the study area (12) showed that the assessment of the general hydrogeological properties was robust, with only minor differences, as the hydraulic conductivities in the hydrogeological maps were based on pumping tests instead of petrographic unit correlations. However, the water table showed considerable differences. This was expected, as the drilling logs covered a large time frame, whereas the isolines in the hydrogeological maps were based on key-date measurements. The density of the supporting points for the interpolation is sparse; thus, the isolines cannot cover small-scale heterogeneity. In addition, only the larger contiguous aquifers were covered by the interpolated isolines.

5.4. Validation of the Flood Dynamics Logic

The logic used to derive the flood dynamics data was tested manually against all gauges in the study area. There were no false negative results, and only one river segment for which manual assessment would have resulted in reduced suitability. This river segment was located at the edge of the study area, with the downstream segments outside the area covered by the gauge data. A test for a smaller study site (Deggendorf County, DE224) yielded a false-positive result for 12 out of 256 segments. These were larger rivers with upstream gauges outside the default search radius of the flood dynamics logic. It is recommended that the search radius should be increased for smaller catchments.

The approximation of the flood dynamics based on the cumulative length leads to a slightly optimistic assessment of the suitability (more areas are considered suitable) as the elevation profile along the river is not considered. This puts the tipping point of suitability downstream. However, the correlation between the catchment area and the cumulative length in the study area was linear in the range of 5–5000 km.

5.5. Completeness of the Site Assessment

This MCDA workflow focused on the technical aspects of a combination of flood protection and drought prevention. Neverthless there are other criteria that influence site assessment.

One criterion not considered in the MCDA is pollution sources near rivers, which determines water quality and thus suitability as a water source. Pollution sources such as sewage treatment plants, industrial dischargers, and contaminated sites pose a risk of contamination to surrounding waters. However, this does not directly affect the site’s suitability near the river, as the abstraction point may be located further downstream or upstream, and tailored treatment of the infiltrated water could be implemented. Furthermore, we generally followed the idea of the Water Framework Directive that all water bodies should be transferred to the best possible state (21). In terms of this MCDA, this implies that only contamination sources that cannot be resolved by technical or natural treatment measures (and within a decent time and cost frame) should rule out sites as a constraint. All other potential sources should be put in a state in which emissions to the river are minimal. These sources would then reduce the suitability.

The resulting site suitability is well suited for identifying potential locations for subsurface floodwater storage schemes. Nevertheless, this assessment can only be supplemented and validated through on-site investigation. In particular, the hydraulic properties of the aquifer, flood dynamics, and the interaction between surface water and the aquifer must be considered. Since the spatial suitability resulting from these criteria is based on selective data, can be very heterogeneous, and is crucial for the feasibility of a scheme, it must be further validated through inspections and studies by experts. An exemplary site description with the respective constraint-mapping analysis can be found in the **Supplementary Material** (available online).

The socioeconomic aspects of the project were not considered in the MCDA. However, these are essential for the successful implementation of storage systems. As a prerequisite for the project is that implementation does not have any long-term negative impacts, a high level of social acceptance is expected. Nevertheless, inconveniences due to construction activities as well as potential risks such as basement flooding or drinking water quality degradation are concerns that need to be addressed. Overlaying the resulting suitability map with interests such as agricultural or financial opportunities can help prioritize sites. Furthermore, priority zones, for example mining, should be taken into account.

5.6. Criteria Selection compared to MAR

The review by Sallwey et al. (55) provides a suitable comparative database to assess the differences in the relevance of criteria between established MAR schemes and combination schemes, as considered in this study. In MCDA studies for MAR until 2018, the focus was on surface properties, whereas in this study, four out of nine criteria belonged to aquifer suitability. This can be attributed to the planned use of existing, technically "extensible" storage opportunities in the geological subsurface. In contrast, the surface is less decisive, as most parts of the storage scheme will not be noticeable. As infiltration takes place in technically designed ditches, the soil properties above the aquifer and, therefore, the leaching of contaminants from soil during infiltration does not need to be considered for technical implementation. This distinguishes Smart-SWS from MAR, Flood-MAR, and Ag-MAR schemes, in which infiltration occurs through the unsaturated zone. Water quantity is partially covered in the review by the hydrometeorology criterion group, which includes precipitation and runoff as harmonized criteria, and the hydrography criteria in the surface group. Nevertheless, river dynamics are not listed as a criterion in any study. The flood dynamics logic developed in this study should facilitate the consideration of rivers as a water source as one criterion for MAR site suitability.

6. CONCLUSIONS

This GIS-based MCDA identified suitable locations for managed aquifer recharge systems that store floodwater, offering an alternative to conventional flood protection systems. Excess floodwater from nearby rivers is infiltrated into existing aquifers using engineered infiltration ditches. In particular, understanding aquifer properties and flood dynamics is of crucial importance for which decision rules were proposed. In this setting, geological and hydrogeological constraints are more challenging compared to other MAR schemes because highly dynamic infiltration is difficult to predict. This limits its application to streams and smaller rivers and is reflected in the final suitability maps. The current design of the proposed Flood-MAR scheme works best with alluvial, fluvial, or glaciofluvial deposits.

The developed workflow was demonstrated for the administrative district Swabia, Germany. Here, approximately 35% of the area was identified as suitable at varying levels. The study area north of the Danube River was less suitable than the area in the south, which was mainly due to the geological settings characterized by low-permeability layers of unconfined aquifers. A sensitivity analysis of the assigned criteria weights showed the high robustness of the underlying data.

The proposed GIS-based MCDA is a robust tool that can be easily extended if new data sources become available. The decision to use only open-access data (including data that require authentication but excluding data that are not available to the general public) makes the workflow versatile and quick. As with any MCDA, the results can never replace a detailed technical site assessment with on-site investigations. The main features that must be validated in the field are the hydraulic properties of the aquifer, flood dynamics, and the interaction between surface water and aquifer. The constraint criteria, on the other hand, are very robust. It should be noted that all criteria can easily be adapted to the specific design of a scheme by modifying the specified thresholds, while some criteria, such as hydraulic gradient or land use, are relatively independent of the detailed plan.

In contrast to a subjective and possibly biased manual site search, MCDA narrows down suitable sites in a robust and transparent way, which can increase acceptance by the general public. The high number of potential sites in the study area is essential and promising, as the replacement of flood prevention dams and basins requires a larger number of the proposed Flood-MAR systems in the upstream catchment. Any of these installations will help maintain the local water balance in times of increasing risk of floods and droughts.

STATEMENTS AND DECLARATIONS

Supplementary Material

Supplementary Material to this article is available online here.

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Author Contributions

Lea Augustin: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, and Writing - review & editing. **Thomas Baumann**: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Validation, and Writing - review & editing.

Conflicts of Interest

The contact author declares that none of the authors have any competing interests.

Data, Code & Protocol Availability

The source code and all links to the data used in this study are available on GitLab (https://gitlab.lrz.de/smart-sws/gis-mcda). This publication was prepared using European Union's Copernicus Land Monitoring Service information; https://doi.org/10.2909/393359a7-7ebd-4a52-80ac-1a18d5f3db9c.

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