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Mapping geosystem services potential for urban climate resilience: A case study from Malmö, Sweden

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ABSTRACT

Urban climate resilience planning often overlooks the subsurface, despite its potential to mitigate flooding, heat stress, and drought. To demonstrate these potentials, we developed thematic Geosystem Service (GS) maps for Malmö, Sweden, to support the integration of the subsurface into climate adaptation strategies. This study identifies GS relevant to the local context, proposes indicators for mapping these services, suggests a methodology for developing GS potential maps and tests the usability of these maps with municipal planners. Six GS related to the subsurface were identified: 1) regulation of coastal erosion, 2) extraction of heat and cold from the subsurface, 3) infiltration and retention of stormwater, 4) provision of subsurface space, 5) provision of groundwater, and 6) provision of construction materials. The findings indicate that GS potential mapping can reveal opportunities to utilise subsurface functions important for climate adaptation, but also show that this capacity is highly uneven across space and often constrained by land use, contamination risks, and technical or legal limitations. Usability testing with planners suggests that the developed GS potential maps may serve more effectively as communicative instruments than as direct planning tools. By illustrating how subsurface services can be systematically incorporated into planning, this research provides a foundation for enhancing the operability of GS in future climate adaptation practices.

1. Introduction

1.1. Background

The Earth's climate is undergoing rapid changes, which may result in increased risks for society (IPCC, 2023; Lavell et al., 2012). Therefore, it is crucial to consider how societies can enhance their resilience in the face of climate change. Climate resilience refers to the ability of a society to plan, absorb, and recover from the impacts of a changing climate (Lavell et al., 2012; Tyler & Moench, 2012). In Sweden, municipalities are entrusted with the practical management of weather-related risks and spatial planning, a responsibility derived from their legally mandated exclusive remit for spatial planning. This stipulates that municipalities must account for natural hazards, such as floods and landslides, in their comprehensive planning (Storbjörk, 2007). Although there is currently no formal obligation to develop climate resilience plans, societal interest is growing, and discussions are underway regarding the potential formalisation of such requirements in response to climate change (see e.g. SFS, 2018:1428). The Swedish planning system is highly decentralised, characterised by non-hierarchical relations between governmental levels and strong municipal autonomy through the planning monopoly, which limits state intervention even when national interests are at stake (Balfors et al., 2018; Blücher, 2013; Hedström & Lundström, 2013). Consequently, municipal land use planning becomes the key arena for implementing national and regional sustainability policies in local contexts (Balfors et al., 2018).

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The subsurface is an important component of climate resilience planning as the functions and services the subsurface provides can mitigate adverse climate impacts. For example, infiltrating and retaining stormwater during heavy rainfall events can delay runoff into potentially flood-prone watercourses. At greater depths, the subsurface maintains a stable temperature, which can be harnessed sustainably for thermal energy storage and retrieval (Erlström et al., 2016), contributing to indoor climate regulation, which is important to reduce heat-related mortality (Sonesson et al., 2024). However, despite that it often holds considerable potential, the subsurface is inadequately addressed in planning processes (e.g. Dick et al., 2017; Finesso & Van Ree, 2022; van der Meulen et al., 2016; Volchko et al., 2020). Reasons for this are likely that planners are often less aware of the functions and services the subsurface provides because of a lack of knowledge or familiarity with the subsurface and associated datasets (Dick et al., 2017). The concept of geosystem services has emerged as a means to bridge this gap (Bobylev et al., 2022). It translates general geological information into practical insights by framing the subsurface in terms of the societal benefits it provides (Norrman et al., 2024). The concept builds upon the well-established framework of ecosystem services, focusing specifically on the subsurface (van Ree & van Beukering, 2016) or abiotic components of nature (Gray, 2011).[1] Lundin-Frisk et al. (2022) identify 22 geosystem services relevant to subsurface planning, which form the backbone of the services considered in this paper.

To facilitate the uptake of geosystem services in planning, it is essential that geosystem service maps are made available. Maps are fundamental to planning as they provide a spatial framework for analysing, e.g. current land use, infrastructure, environmental conditions, and risk zones, and thus enable planners to identify vulnerable areas and implement protective measures, ensuring safer and more resilient developments. Maps are also what most planners are familiar with, and hold an 'air of authority' (e.g. Hauck et al., 2013). Yet maps with geological and subsurface data are often not directly applicable or easily interpretable by planners without specialised knowledge (Dick et al., 2017). On the other hand, geosystem services are rarely represented cartographically, which limits the practical application of geosystem services as a concept.

There is growing interest in mapping ecosystem services as their integration into planning becomes increasingly implemented (e.g., Potschin et al., 2016). Such maps typically rely on indicators with spatial data (e.g., Grima et al., 2023). Previous work developed national-scale indicators for geosystem service potentials in Sweden (Lundin-Frisk et al., 2025), which were subsequently adapted to create geosystem service maps in a climate resilience planning context. Adaptation is essential because resilience indicators are context-dependent and shaped by data availability (Cariolet et al., 2019).

This paper presents a novel operationalisation of the geosystem services concept through the development of thematic maps of the potential for geosystem services relevant to urban climate resilience planning. In addition, this study further advances the field by empirically testing the usability of the developed maps with municipal planners in Malmö, generating practitioner-informed insights into their practical value and limitations. This dual approach, combining methodological innovation with stakeholder engagement, marks an important step toward integrating geosystem services into mainstream planning processes and enhancing the visibility of the urban subsurface in climate adaptation strategies.

[1] There is an ongoing discourse regarding the definition of geosystem services. Two prominent definitions are frequently cited: beneficial contributions provided by the subsurface (see van Ree & van Beukering, 2016) or abiotic nature (see Gray, 2013) to human well-being. For a review of the concept, see Lundin-Frisk et al., 2022.

1.2. Aim and objectives

The overall aim of this paper is to develop spatial subsurface information, i.e. maps, that can effectively support the integration of subsurface information in climate resilience planning. To achieve this aim, the study has two specific objectives: i) to develop geosystem services potential maps that link the 'geophysical environment'[2] to geosystem services relevant for climate resilience planning, and ii) to investigate the usability and added value of these maps with targeted end users, using the city of Malmö, Sweden, as a pilot study.

2. Study area

The City of Malmö (or Malmö municipality) is situated near the southwestern tip of Sweden (13°00′ E, 55°35′ N), within Scania (Skåne in Swedish) County (Fig. 1). It is the third largest city in Sweden with approximately 365,000 inhabitants and is experiencing rapid growth, increasing at an annual rate of 1–1.5 %. Being part of the Öresund Region, it is connected to Copenhagen, Denmark, via the Öresund Bridge. The climate is oceanic with mild winters and cool to warm summers, and is subject to strong winds and moderate precipitation (Beck et al., 2018; Persson et al., 2012). The region's geography includes clayey plains, forested hills, and a complex bedrock structure divided by the Sorgenfrei-Tornquist Zone, with overburden formed during the Quaternary period (Stephens, 2020; Wastenson & Fredén, 2002). While some parts of Sweden are experiencing tectonic uplift, Malmö is undergoing relative land subsidence (Chen et al., 2017; Poutanen & Steffen, 2014; Vestøl et al., 2019). A more detailed description of Sweden's and Malmö's geological setting is presented in the Supplementary Material (SM).

The City of Malmö is developing a climate resilience plan to address projected impacts from climate change, including sea level rise, heavy rainfall, heatwaves, and drought. Measures are intended to be multifunctional and integrated into the urban landscape. The challenges that the City of Malmö is expected to face under the Representative Concentration Pathway (RCP) of 8.5, along with ongoing countermeasures, are presented in detail in the SM, and summarised here. The challenges can be subdivided into four climate-related themes. Firstly, a sea level rise of +2.71 m during a 200-year high-water event is anticipated, necessitating protective measures along its 43-km coastline. Secondly, heavy rainfalls are expected to become more frequent and intense, particularly in winter, with the most extreme events in summer (Persson et al., 2012). Malmö's downpour plan requires infrastructure to manage 100-year rainfall events, and identifies urban densification and impermeable surfaces as key contributors to flooding risk (Malmö stad, 2016). Thirdly, heatwaves are projected to increase in frequency, duration, and intensity, with the number of days exceeding 25 °C increasing (Sonesson et al., 2024). Urban heat island effects are a concern, particularly in densely built areas with limited greenery (Deilami et al., 2018). Finally, although Sweden is generally less affected by drought compared to many other nations (e.g. Sjökvist et al., 2019), Malmö is expected to face growing challenges related to water scarcity. The city's main drinking water supply, sourced from Lake Bolmen, Lake Vombsjön, and the Alnarpsströmmen aquifer, is currently seen as providing a stable supply (Sonesson et al., 2024). However, a drought in 2018 caused smaller watercourses and water bodies to experience critically low levels, and agricultural land and local ecosystems were severely affected (Sjökvist

[2] 'Geophysical' in this context refers to the mainly physical characteristics of the Earth, including its formation, evolution and the processes that shape Earth. This includes for example, geological formations, geomorphological landforms, and (ground)water. These services have been relabelled as geophysical services in CICES, (Haines-Young, 2023). Please note that there is also ongoing work to broaden the geodiversity taxonomy and link it to geosystem services (Hjort et al., 2024; van Ree et al., 2024).

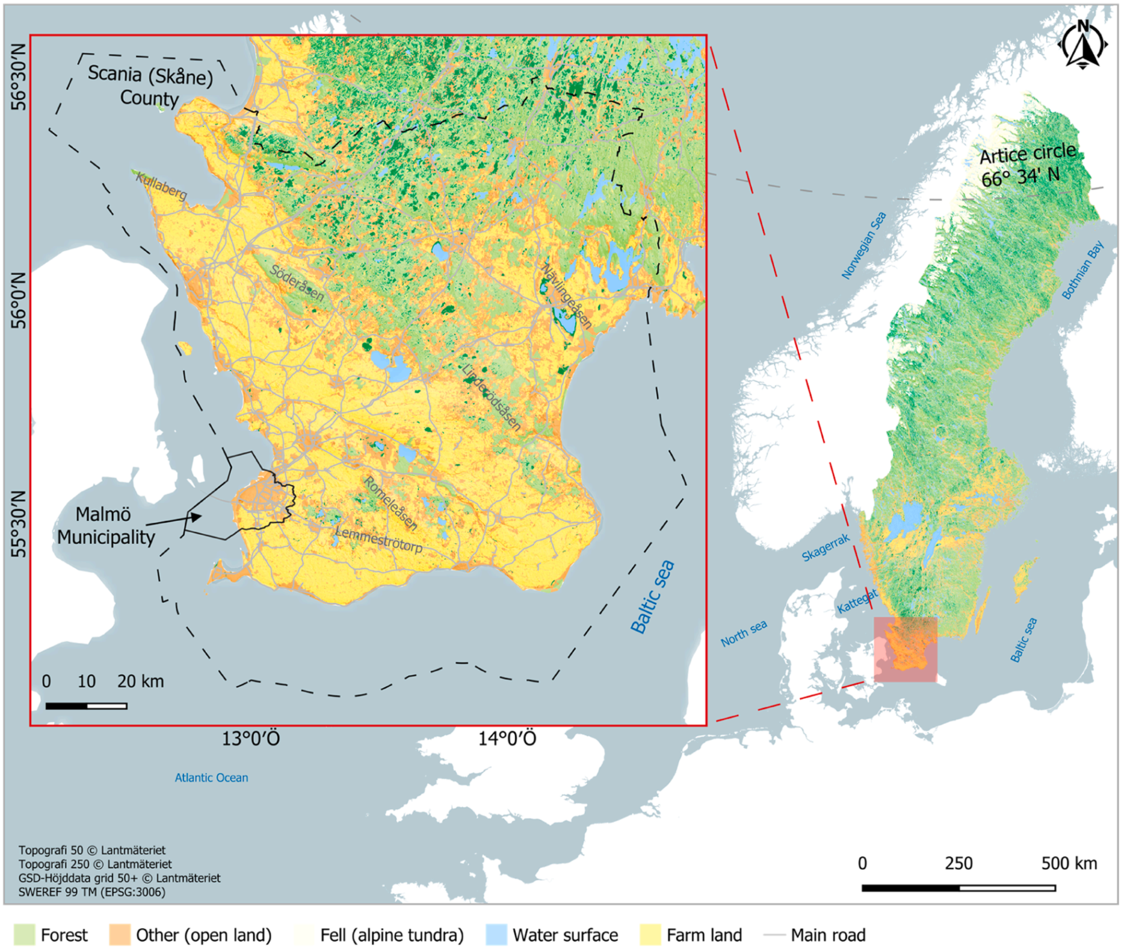

Fig. 1. Overview map of Scania and the study area (Malmö municipality).

et al., 2019).

3. Method

The methodology employed in this study comprises two main components. First, geosystem service potential maps were developed to represent spatial variations in service provision. Second, these maps were evaluated through a participatory process involving planners, after which they were revised based on the feedback received. Fig. 2 provides a schematic overview of the steps taken and the methods applied in the study.

3.1. Development of geosystem service maps

The following methodology was used to create the geosystem services maps and consists of three steps. The approach is loosely based on ecosystem services mapping methods (e.g., Andersson-Sköld et al., 2018; Baró et al., 2016) and conceptually aligns with other point-based systems applied to geological and geomorphological features (e.g., Bathrellos et al., 2012; Depountis, 2023).

Step 1 – Selection of relevant geosystem services

Step 1 involved selecting geosystem services considered relevant for the City of Malmö's climate resilience planning efforts. The selection process began by identifying pertinent services from the comprehensive list of geosystem services presented in Lundin-Frisk et al. (2022). This initial screening was informed by the discussions held during WS1, as well as subsequent internal deliberations among the authors. The final selection was guided by three key considerations: i) the four climate-related thematic areas defined by the City of Malmö, rising sea levels, heavy rains, heat, and drought; ii) general knowledge of the local geology and geomorphology, particularly how these physical characteristics underpin beneficial processes and functions (e.g. the influence of water velocity on erosion, sediment transport, and deposition); and iii) examples of established solutions implemented in other contexts, such as the Stormwater Management and Road Tunnel (SMART) in Kuala Lumpur, Malaysia.

Step 2 – Linking the 'geophysical environment' to the potential to deliver geosystem services

Step 2 involved four subsequent sub-steps (a-d) to link the 'geophysical environment' to the potential to deliver a specific geosystem service using geosystem services indicators (Lundin-Frisk et al., 2025). To derive the final 'effective geosystem services potential', the potential of the geophysical environment to deliver a specific service is combined with a suitability and an accessibility assessment.

Step 2a entailed superimposing a cartographic grid on the study area, with each cell in the grid measuring 10 by 10 m The grid resolution in this study is based on Andersson-Sköld et al. (2018), which employed a similar methodological framework to assess urban ecosystem services in another Swedish municipality (Gothenburg municipality). However, for information regarding the spatial distribution of subsurface infrastructure, a larger grid (300 m by 300 m) was applied in this study to prevent the disclosure of classified subsurface information. The grid determines over which area a single value is assigned, based on the geographical information in each cell.

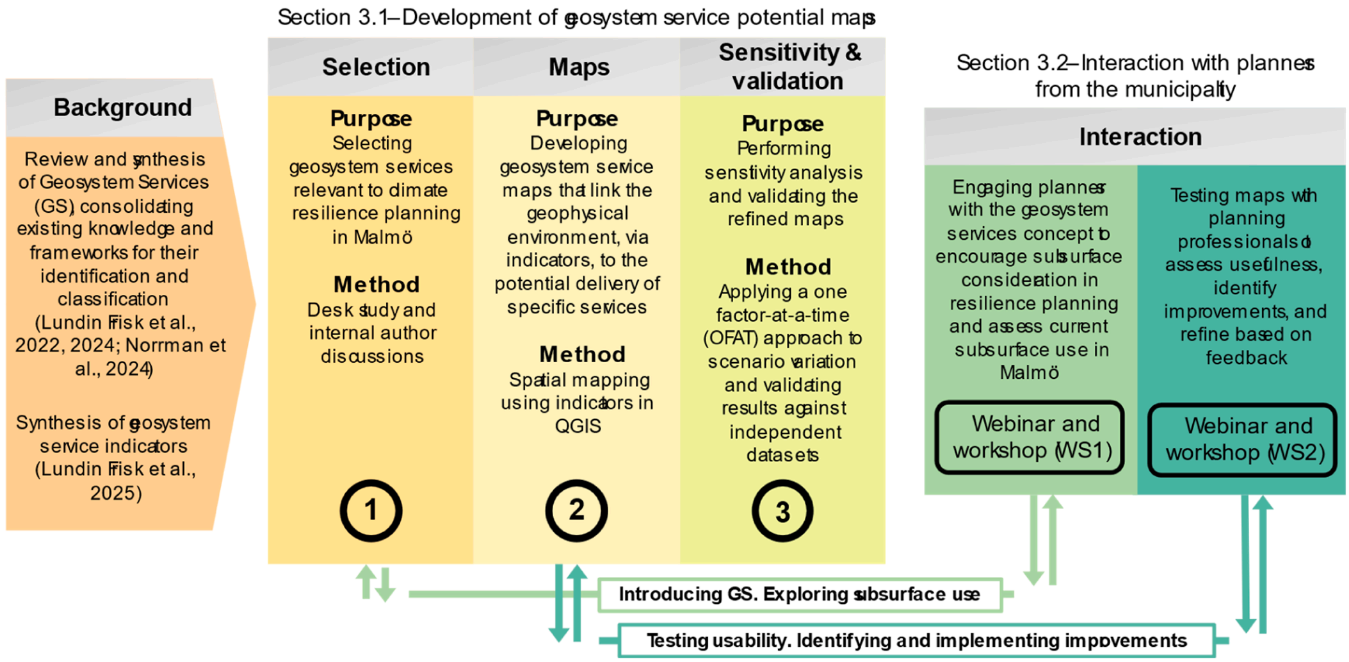

Fig. 2. Schematic overview of the working process and the methods used to achieve the research aim and objectives.

Step 2b entailed estimating the potential supply of geosystem services in each cell. This was achieved by linking distinct geophysical environments, represented by indicators, to their capacity to provide specific geosystem services. Each geophysical environment is characterised by attributes such as soil[3] or rock type, soil depth, location of fracture zones and groundwater level, with a given spatial distribution. The potential supply of a geosystem service in a cell is the combination of: i) the presence and spatial extent of a specific geophysical environment, and ii) the inherent capacity of that environment to contribute to the delivery of a specific geosystem service. The potential contribution of each parameter to the supply of a specific geosystem service is categorised using a capacity class system, ranging from Class D (no or limited capacity; numeric value 0) to Class A (highest capacity; numeric value 3). Intermediate levels are defined as Class C (some capacity; value 1) and Class B (moderate capacity; value 2). A comprehensive overview of the capacity assigned to each parameter, for each service, is provided in the SM (see Table 1 for a list of the capacity classes). Please note that the scale is ordinal and based on expert judgement or literature, relative to the study area. It is not an absolute measure of capacity. Because the capacity classes used in this study (A–D) are ordinal rather than interval-scale, a consistent non-compensatory aggregation logic is applied across all services. Compensatory methods such as averaging would incorrectly imply numerical relationships between classes and could create contradictory interpretations, particularly where Class D represents a failed prerequisite. The min-rule is therefore used wherever aggregation is required.

The indicators used are based on the comprehensive list in Lundin-Frisk et al. (2025) but adapted and modified to better reflect the conditions of the study area (see SM for a list of indicators used and adaptations made for each service). These adaptations were informed by internal discussions among the authors, drawing on general knowledge of the local geology and geological processes, and on the spatial information available. Most indicators are based on a combination of several parameters that collectively reflect the potential to supply a given service. Thus, to estimate the potential supply of a specific geosystem service within a given cell, the geophysical environment that occupies

Table 1
List of capacity, accessibility and suitability classes.

Class	Label		Description
Capacity to supply a given geosystem service indicated by a given indicator	A (3)	Highest capacity	High contribution to the supply of the given geosystem service
	B (2)	Moderate capacity	Moderate contribution to the supply of the given geosystem service
	C (1)	Some capacity	Some contribution to the supply of the given geosystem service
	D (0)	No or limited capacity	Limited contribution to the supply of the given geosystem service
Accessibility	N/A	No restrictions in terms of accessibility	Does not present meaningful restrictions to the provision of the service
	C (1)	Limited accessibility	Imposes some limitations on the provision of the service, but not to a prohibitive extent
	D (0)	Inaccessible	Significant constraints that preclude the provision of the geosystem service
Suitability	N/A	No restrictions in terms of suitability	Does not present meaningful restrictions to the provision of the service
	C (1)	Conditionally suitable	Imposes some limitations on the provision of the service, but not to a prohibitive extent
	D (0)	Unsuitable	Significant constraints that preclude the provision of the geosystem service

Note: The scale is ordinal and based on expert judgment or literature. It is relative to the study area and not an absolute measure of capacity.

[3] The term 'soil' has different connotations in various subject areas. In this study, soil refers to 'a mostly unconsolidated assemblage of particles that are affected by physical, chemical, and/or biological processes at or near the planetary surface'.

the largest proportion of this cell is first identified. The indicator parameters for each geosystem service are aggregated using a non-compensatory "minimum value" (min-rule) approach. This means that the overall potential supply of a service in a grid cell is determined by the parameter with the lowest capacity value. This approach is used since each parameter in the indicators represents a necessary condition for the provision of the geosystem service. If any one condition is not met, the service cannot be supplied, and other favourable parameters cannot compensate. Accordingly, the potential supply of a specific geosystem service is calculated using the following equation:

$$G_i = \min_{j=1,\dots,n}\left(k_{i,j}\middle|g_{i,j} = \mathrm{mode}\left(g_{i,j}\right)\right) \quad \text{(i)}$$

where G_i represents the potential supply of a geosystem service in grid cell i, n is the number of parameters included in the indicator, $mode\left(g_{i,j}\right)$ denotes the dominant geophysical environment in grid cell i (that is, the environment type covering the largest area) for each included parameter j in grid cell i, and $k_{i,j}$ is the capacity of the dominating geophysical environment to supply a given geosystem service, ranging from no or limited capacity to highest capacity (see Table 1).

This approach aligns with established geological and geomorphological principles. For example, the indicator for "stormwater infiltration" combines three key parameters ($j = 3$): soil type ($g_{i,1}$), sandy soils, with their coarse texture, allow rapid infiltration, while clayey soils, being fine-grained and compact, have much lower infiltration rates; soil depth ($g_{i,2}$), sufficient depth is necessary to retain meaningful volumes of water, as thin layers may not provide adequate storage; and groundwater level ($g_{i,3}$), if the groundwater table is close to the surface, the soil becomes saturated, leaving little or no unsaturated zone for infiltration and retention, regardless of soil type or depth. In addition, the capacity classes ($A = 3$ to $D = 0$) are ordinal, not interval. Arithmetic averaging or multiplicative aggregation of ordinal values can produce misleading results (e.g., averaging "A" and "D" to "B" is not meaningful when "D" represents a failed prerequisite). The min-rule preserves the order semantics and reflects the practical reality that if a prerequisite is absent, the service is unavailable.

The minimum-value (min-rule) approach was adopted because these maps are intended for comprehensive (strategic) planning, where data and time are limited and early-stage screening must be transparent and conservative (see e.g. Andersson-Sköld et al., 2018; Norrman et al., 2021). More advanced methods, such as fully coupled 3D geological or process models that resolve subsurface heterogeneity and interactions and can be used for quantification of service supply, would be preferable (e.g. Schokker et al., 2017). However, such approaches require detailed local datasets that are not available at a city or municipal scale and cannot currently be operationalised for all services. Therefore, a clear limiting-factor rule is the most defensible and practical choice: it reduces the risk of false positives, aligns with known physical bottlenecks, and might be easier for planners to interpret and apply in practice.

Step 2c entailed assessing the suitability for, and accessibility to, the potential of a specific geosystem service in each cell. The potential supply of a given service is not only contingent upon the inherent potential of the geophysical environment to supply said service, but also on whether it is suitable to utilise the service and on how accessible it is. To exemplify, a given environment (e.g. a filling material in an urban area with coarse material) may have a high potential to infiltrate and retain stormwater. However, this potential may not be suitable to utilise due to contamination concerns, or it may be inaccessible due to the presence of an impermeable surface cover such as asphalt. The suitability and accessibility for an indicator are assigned a value from suitable and/or accessible to unsuitable and/or inaccessible (see Table 1). The suitability and accessibility classification was determined by internal discussions among the authors, taking into account i) general knowledge of common accessibility and suitability concerns and ii) assessments on said concerns by others (see e.g. Grånäs et al., 2013; Göransson & Lindgren, 2024; Schoning & Lundqvist, 2020 for assessments related to accessibility in the context of geomaterials). Accordingly, the effective potential (E_i) to supply a specific geosystem service, i.e. the potential that is actually available for utilisation, is the minimum value of the potential (G_i), and the suitability (S_i) and accessibility (A_i) classification. This classification is based on suitability and accessibility indicators (s, a) that for some services consist of several independent attributes (e.g. land use, contaminated sites, and proximity to Natura 2000 areas) that together reflect the suitability and accessibility related to the given service (see SM for a detailed overview and Table 1 for a list of the accessibility and suitability classes). The attribute assigned to a grid cell is equal to the attribute with the largest area proportion in this cell. Accordingly, the effective potential is calculated as follows for each individual cell:

$$E_i = \min\left(G_i,\ s_i \mid s_i = \mathrm{mode}\left(s_{i,m}\right),\ \ a_i \mid a_i = \mathrm{mode}\left(a_{i,l}\right)\right) \quad \text{(ii)}$$

where E_i is the effective potential of a specific geosystem service in cell i, G_i is the potential supply of the geosystem service in cell i, as defined in Equation (i), $\mathrm{mode}\left(s_{i,m}\right)$ is the suitability value based on the attribute with the largest area proportion in cell i, $\mathrm{mode}\left(a_{i,l}\right)$ is the accessibility value based on the attribute with the largest area proportion in cell i, and m and l denotes that suitability and accessibility indicators for some services consist of several independent attributes.

Finally, *step 2d* involved creating maps of the potential supply of each specific geosystem service using the open-source software QGIS (version 3.34.12 "Prizren"). For each service, two maps were produced: one illustrating the potential supply (G_i), and another incorporating assessments of suitability and accessibility, illustrating the effective potential supply (E_i). An example is illustrated in Fig. 3, for the specific geosystem service 'infiltration and retention of stormwater'.

Step 3 – Conducting sensitivity analysis and validation of the refined maps

Step 3 involved performing a sensitivity analysis in QGIS by systematically adjusting input parameters and comparing alternative scenarios. The objective was to examine how changes in assumptions, such as treating filling materials as having low rather than high infiltration capacity, affect the resulting maps. In each scenario, capacity class values were shifted one to two levels up or down from their original values, following a one-factor-at-a-time (OFAT) design, enabling identification of the parameters exerting the greatest influence on the final maps. Please note that in the sensitivity analysis, shifting a class "up" or "down" simply means assigning it to an adjacent category (e.g., C to B or D), not performing a numerical calculation. These scenarios test alternative categorical classifications, not interval-based adjustments, ensuring consistency with the ordinal nature of the indicators. Futhermore, this step also included validating the maps against independent datasets to assess their reliability.

Two complementary metrics were employed in the sensitivity analysis: the range-based Normalised Average Root Mean Square Error (NARMSE) and the Map Disagreement Index (MDI). The approach broadly follows the steps outlined by Schulp et al. (2014) for assessing the sensitivity of ecosystem service maps. For further discussion on normalised error metrics and disagreement indices, as well as their interpretation in spatial mapping and modelling, see Pontius (2022) and Verma et al. (2020).

The Root Mean Square Error (RMSE) measures the average magnitude of differences between a scenario map and a reference map. To make this measure comparable across datasets and scales, RMSE was

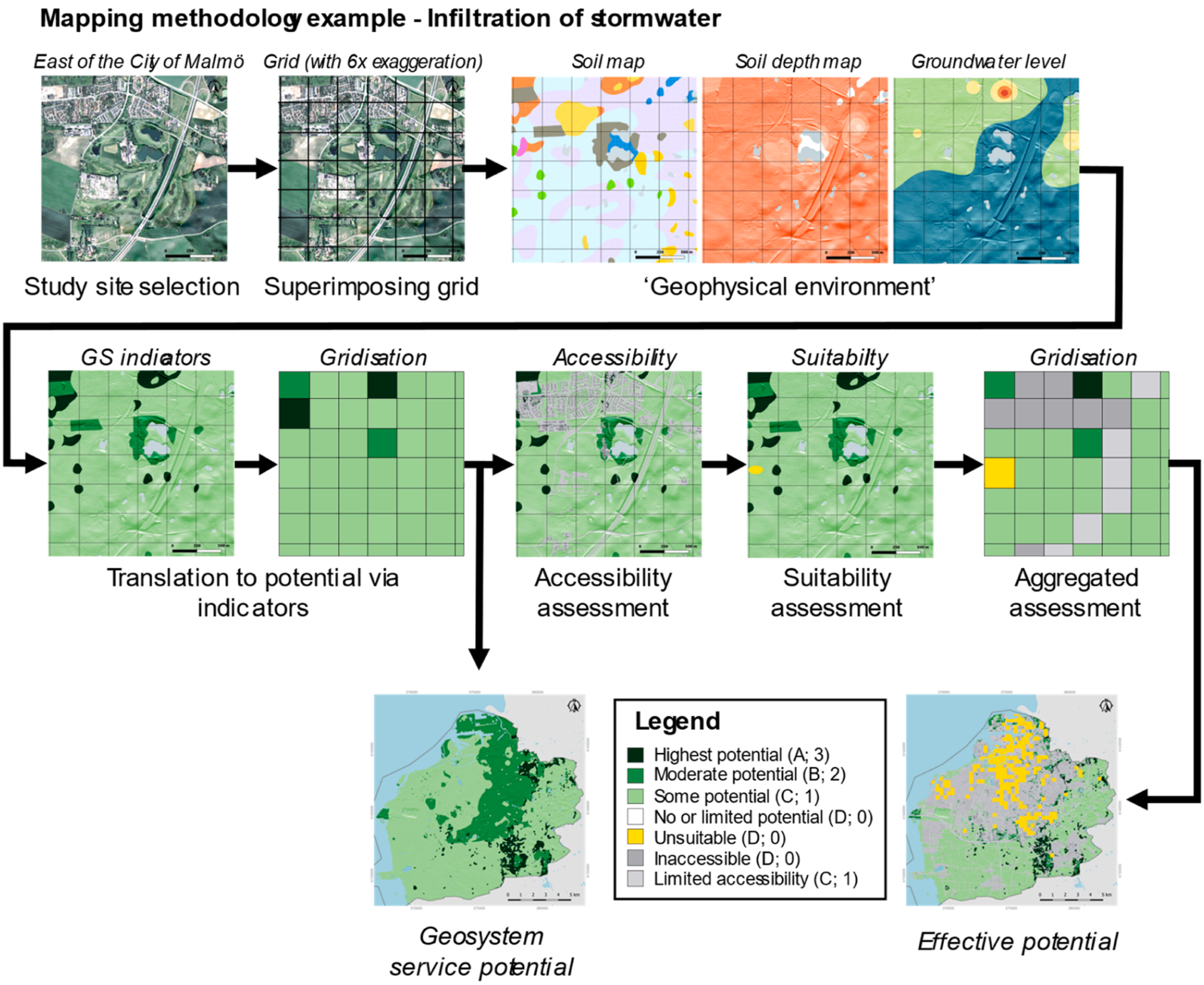

Fig. 3. Schematic illustration of the map creation process.
Note: See SM for indicators used. Abbreviations used in the figure: Geosystem Service (GS).

normalised by the max and min values of the reference raster:

$$NA - RMSE = \frac{\overline{RMSE}}{R_{max} - R_{min}} \quad \text{(III)}$$

where $\overline{RMSE}$ is the mean RMSE across all scenarios, and $R_{max} - R_{min}$ is the value range of the reference raster (= 3). NA-RMSE provides a normalised, unitless measure of deviation from the baseline, and is used to answer how far scenarios deviate from the basemap. Values near 0 indicate that scenarios closely match the basemap (reference).

While NA-RMSE focuses on deviations from a single reference, MDI summarises internal consistency among all maps. It is based on the Average Pairwise RMSE ($AP - \overline{RMSE}$) across all unordered pairs of maps (including the reference):

$$AP - \overline{RMSE} = \frac{2}{t(t-1)} \sum_{i<j} \sqrt{mean(M_{base} - M_{scenario})^2)} \quad \text{(IV)}$$

where t is the total number of maps analysed (scenarios + reference), M_{base} is the basemap and $M_{scenario}$ is a scenario map (see SM for details on the different scenarios tested).

The MDI normalises $AP - \overline{RMSE}$ by the global range of values across all maps:

$$MDI = \frac{AP - \overline{RMSE}}{R_{max} - R_{min}} \quad \text{(V)}$$

where $\overline{RMSE}$ is the mean RMSE across all scenarios, and $R_{max} - R_{min}$ represents the value range of the reference raster. The MDI quantifies the overall disagreement among maps on a 0–1 scale, indicating whether uncertainty is concentrated in a few scenarios or widespread. An MDI close to 0 suggests that maps are nearly identical, whereas an MDI near 1 indicates differences as large as the entire value range.

In broad terms, lower NA-RMSE and MDI values indicate higher similarity and lower sensitivity to parameter changes. However, these metrics do not capture deviations from the actual provision of geosystem services (see e.g. Schulp et al., 2014). To address this, the developed maps were also validated by comparing them against independent datasets that serve as proxies for geosystem service supply. It is expected that areas with higher potential will overlap with these independent proxies, and such spatial coincidence is interpreted as an indication of model quality. The degree of overlap is expressed as a percentage for each potential capacity class (highest, moderate, some, and no or limited potential). Table 5 in section 4.3.2 presents a summary of the independent datasets used for comparison, and outlines the assumed relationships between their values and those of the geosystem service maps.

Table 2
The following services were identified as capable of contributing to the urban climate resilience themes in the city of Malmö.

Geosystem service	Specific service	Specific use	Theme(s)			
			Rising sea levels	Heavy rain	Heat	Drought
Regulation of erosion	Regulation of coastal erosion	Use of rocks' and soils' inherent capacity to resist erosion	✔			
Regulation of water quantity	Infiltration and retention of stormwater	Use of the subsurface for infiltration and retention of stormwater to reduce flooding	(✔)	✔	(✔)	(✔)
Regulation of temperature by the subsurface	Retrieval of heat or cold from the subsurface	Use of Borehole Thermal Energy Storage (BTES) system to extract heat or cold			✔	
Provisioning of subsurface space	Availability of subsurface space	Use of the shallow subsurface [<10 m] to place vertical and horizontal constructions		✔	✔	
		Use of the deep subsurface to place vertical and horizontal constructions		✔	✔	
Provisioning of groundwater	Withdrawal of groundwater	Use of groundwater for drinking water supply				✔
		Use of groundwater for process water supply (e.g. irrigation)				✔
Provisioning of construction materials	Retrieval of construction materials	Use of inorganic aggregates for concrete production	✔	(✔)	(✔)	(✔)
		Use of inorganic materials for filling purposes (e.g. macadam)	✔	(✔)	(✔)	(✔)

Note: Services that can be used to directly enhance climate resilience are marked with ✔, whereas services that can contribute indirectly are marked with (✔). Not all indirect services are included in the analysis for this study. For details on how these specific services can contribute to climate resilience, please refer to the SM.

Table 3
Summary of indicators used to create the Geosystem Service (GS) potential maps.

Geosystem service	Specific service	Specific use	Benefit	Geophysical parameters (g_j) included in GS potential indicators	Attributes included in accessibility (a_j)	Attributes included in suitability (s_j)
Regulation of erosion	Regulation of coastal erosion	Use of the natural environment to mitigate transgression	Lowering of risks associated with sea-level rise	Soil lithology [-] Estimated sea-level rise [m]	N/A	N/A
Regulation of temperature by the subsurface	Retrieval of heat and cold from the subsurface	Use of the subsurface via Borehole Thermal Energy Storage (BTES) to regulate indoor climate	Comfortable indoor climate	Lithological units [-]	Soil depth [m] Conflicting subsurface space [-] Conflicting surface use [-]	N/A
Regulation of water quantity	Infiltration and retention of stormwater	Use of the subsurface to infiltrate and retain stormwater	Lowering of flooding risks	Permeable soils [-] Unsaturated zone thickness [m] Soil layer thickness [m]	Impermeable surfaces [-], Conflicting surface use [-]	Contaminated sites [-]
Provisioning of subsurface space	Availability of deep subsurface space	Use of the deep subsurface to place vertical and horizontal constructions	Supply of physical space in the deep subsurface to place constructions	Subsurface infrastructure density [m^3/m^2]	Conflicting subsurface space [-], Lineament density [n], Soft ground thickness [m]	N/A
	Availability of shallow subsurface space	Use of the near-surface subsurface to place vertical and horizontal constructions	Supply of physical space in the shallow subsurface to place constructions	Building density [n/100m^2]	Conflicting surface use [-]	N/A
Provisioning of groundwater	Withdrawal of groundwater	Use of water from the subsurface	Supply of fresh water	Groundwater withdrawal capacity [m^3/d]	Conflicting surface use [-], Protected areas [-]	Contaminated sites [-]
Provisioning of construction materials	Retrieval of construction materials	Use of geomaterials as construction aggregates	Supply of materials needed for construction	Lithological units [-]	Conflicting surface use [-], Protected areas [-]	N/A
				Soil deposits [-]	Soil layer thickness [m]	N/A

Note: See SM for details on the indicators used, associated capacity classes, data availability, and justification for each service. Please note that some indicators are indices of several parameters, e.g. permeable soils, unsaturated zone thickness and soil layer thickness. Legend: N/A Not Applicable, [-] dimensionless, [m] meter, [m^3] cubic meter, [m^2] square meter, [n] number of something, [d] day as in 24 h.

3.2. Interaction with planners from the municipality

3.2.1. Introducing geosystem services as a concept

Introducing geosystem services to urban planners aimed to encourage reflection on the role of the subsurface in resilience planning and to gather insights into current subsurface use in Malmö. This was achieved through a webinar (March 7, 2024) and a workshop (WS1, March 18, 2024). The workshop supported the selection of geosystem services relevant to the study setting and context and involved 15 participants from diverse professional backgrounds, all sharing an interest in urban planning, climate resilience, climate adaptation, ecosystem services, and sustainability. Most participants were employed by the City of Malmö, while others represented the private real estate sector. The workshop focused on discussing how geosystem services could be used to enhance climate resilience.

Participants were divided into four groups to address three main topics: (1) present-day examples of geosystem services in Malmö, (2) future possibilities for utilising geosystem services and the subsurface to enhance climate resilience, and (3) potential risks and solutions associated with these services. To support the discussions, participants were provided with two maps illustrating climate-induced risks, extreme heat and flooding in different areas of Malmö, which they were already familiar with (see SM for details on the workshop setup and maps).

3.2.2. Testing and refining the developed maps

Building on the initial introduction of geosystem services and the insights gathered during WS1, a second phase focused on evaluating the usability of the developed maps and obtaining feedback for improvement. To this end, a subsequent webinar and workshop (WS2) were conducted to gather input from presumed 'end users' regarding the usability and perceived added value of the geosystem service potential maps within a planning context. This feedback was then used to refine the maps, aiming to enhance both their readability and practical applicability.

The workshop included 7 participants, all of whom were municipal civil servants engaged in urban planning, climate resilience, and sustainability, representing 'end users' that could potentially benefit from the developed geosystem services maps. During WS2, the participants received a brief introduction to the maps (see SM for details) and were divided into smaller groups to discuss their usability and added value in comprehensive planning processes. To guide the discussion, participants were provided with five questions:

a) Can the information in the developed maps be used in climate resilience adaptation planning?
b) Can the information in the developed maps be used in other types of planning (e.g. detailed development or comprehensive planning)?
c) Is there a need for clarification of the map? If so, what?
d) Do you perceive a practical application for geosystem service maps in your current work? Please specify your answer.
e) Other comments regarding this map? For example, are there any obstacles to developing and using these types of maps in the current planning processes? At what planning level can these maps be helpful?

Feedback was collected through small-group discussions and subsequently translated and synthesised by the research team. The approach was pragmatic and user-centred, focusing on identifying recurring themes, actionable suggestions, and specific usability concerns relevant to the development of geosystem service maps. The synthesised feedback (see SM for the full responses) was circulated to participants for validation prior to analysis, ensuring that minority perspectives were not overlooked or misrepresented. Given the exploratory nature and relatively small size of the participant group, we prioritised actionable feedback over formal consensus measurement. This approach was chosen to maintain clarity and brevity in reporting, while ensuring that the feedback loop between end users and map developers was clearly documented and refinements were traceable to specific user input.

4. Results

This section presents the findings from the two main components of the study: the development of geosystem service potential maps and their evaluation through interaction with municipal planners. The results begin by explaining how geosystem services were connected to urban climate resilience in Malmö, providing the conceptual basis for interpreting the findings. This is followed by a description of the developed geosystem service potential maps. The section then outlines the sensitivity analysis and validation procedures used to assess the robustness and reliability of the mapping approach. Finally, it summarises feedback from municipal planners on the usability and practical value of the developed maps in supporting planning and decision-making processes.

4.1. Connecting geosystem services to urban climate resilience of the city of Malmö

Table 2 highlights those geosystem services that were deemed to be most relevant to include in climate resilience planning for the City of Malmö. For a detailed rationale behind the selection of geosystem services, and an explanation of how they may help mitigate certain climate change impacts in line with the four themes prioritised by the City, please refer to the SM.

4.2. Developed maps of geosystem service potentials

Table 3 lists the indicators that are used to create the geosystem services potential maps. The maps presented in the results section are the revised versions, which incorporate feedback and refinements made following the second workshop (WS2). For reference, the original maps shown during the workshop are available in the SM.

4.2.1. Potential for regulation of coastal erosion

Fig. 4 presents the baseline map for Regulation of coastal erosion potential and the effective potential. To view the details on indicators and classes used, see SM. The map is based on a generalised erosional resistance potential of different types of geological materials (Malmberg Persson et al., 2016; Nyberg et al., 2021) and modelling of sea encroachment at a 3 m rise of the mean sea level (MSL). The map identifies areas within the municipality that are resistant to coastal erosion. Approximately 15 % of the municipality is classified as having some potential (Class C), while 53 % falls into the moderate class (Class B) and 32 % into the highest class (Class A), with higher-potential areas concentrated in the north-western part of the municipality due to widespread use of anthropogenic materials.

In terms of effective potential, examining the buildings within the study area, the majority (76 %) are situated in locations >5 m above the current sea level. Among the buildings located below 5 m and therefore expected to be affected by rising sea levels and increased coastal erosion, the largest share falls within the moderate (10 %) and highest risk classes (10 %) in the north-western part of the municipality. Further south, along the sandy beaches, there are houses (4 %) that are positioned in areas that are both below the projected sea-level rise and composed of erodible materials.

4.2.2. Potential for retrieval of heat and cold from the subsurface (geoenergy wells)

Fig. 5 presents the baseline map for the potential to retrieve heat and cold from the subsurface via Borehole Thermal Energy Storage (BTES) systems, as well as the effective potential. Details on indicators and classes used are presented in SM. The map is based on thermal conductivity estimates for generalised rock units (Erlström et al., 2016) and the presence of lineaments (e.g. faults), where increased flow rates and groundwater turnover times are assumed. The BTES systems are expected to be rather shallow systems (often with a depth <60 m) as is common in the specific study setting, and, thus, only a limited geothermal influence is expected. In broad terms, the potential to extract heat and cold via BTES systems in the municipality is on the lower end. However, some areas have a higher potential, and this potential is relatively accessible due to limited competition from other subsurface installations and a thin soil cover (i.e. effective potential).

Approximately 66 % of the municipality is classified as having some

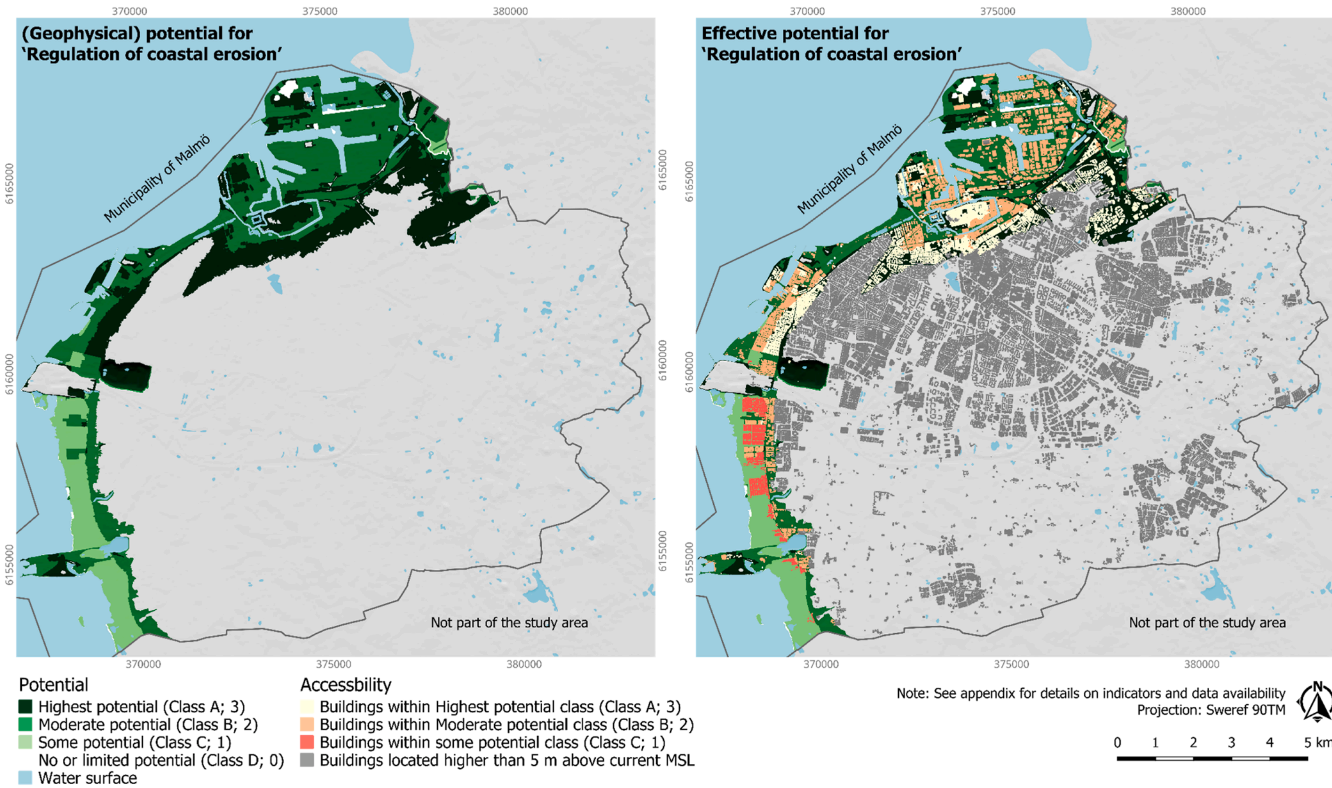

Fig. 4. Baseline map of the potential for Regulation of coastal erosion (left) and map showing the effective potential (right).
Note: See SM for indicators used. Abbreviations used: Mean Sea Level (MSL).

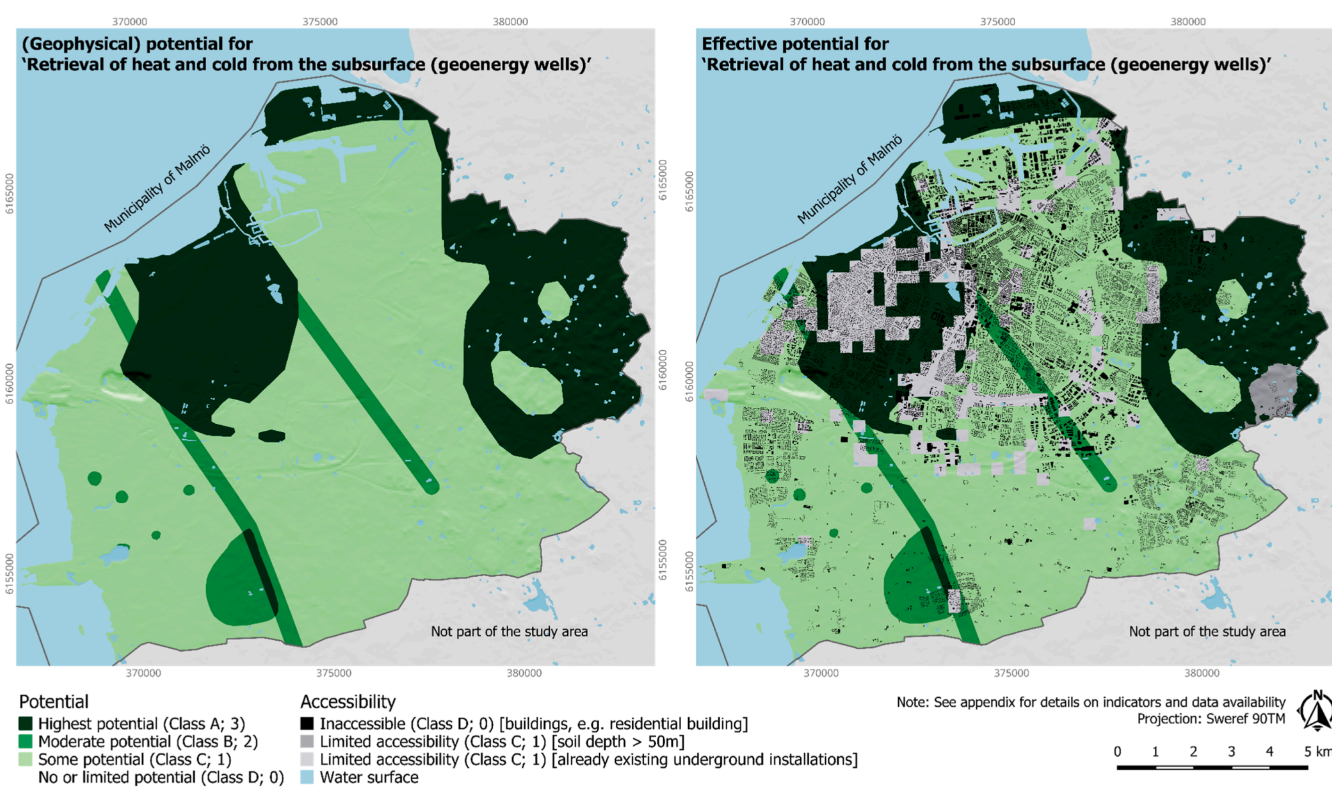

Fig. 5. Baseline map of the potential for Retrieval of heat and cold from the subsurface (geoenergy wells) (left) and map showing the effective potential (right).
Note: See SM for indicators used.

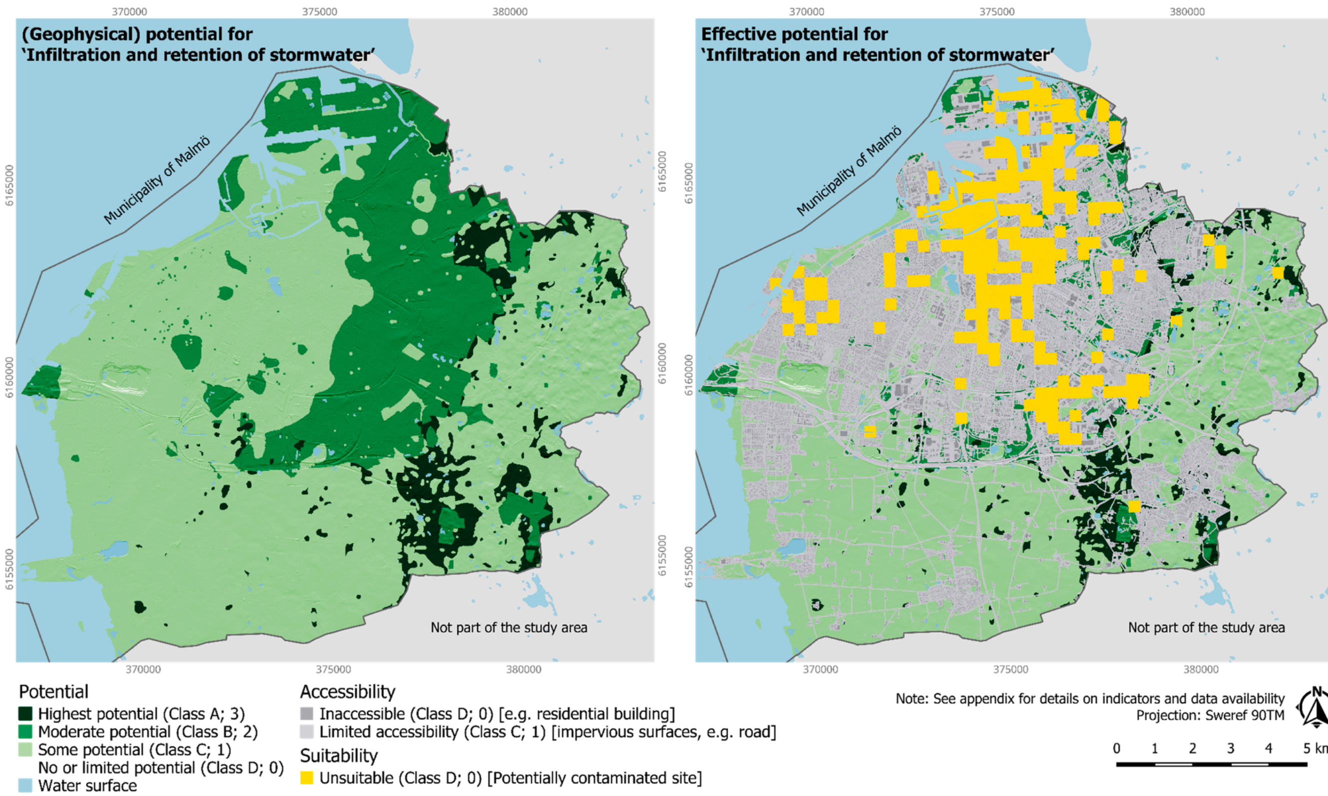

Fig. 6. Baseline map of the potential for Infiltration and retention of stormwater (left) and map showing the effective potential (right).
Note: See SM for indicators used.

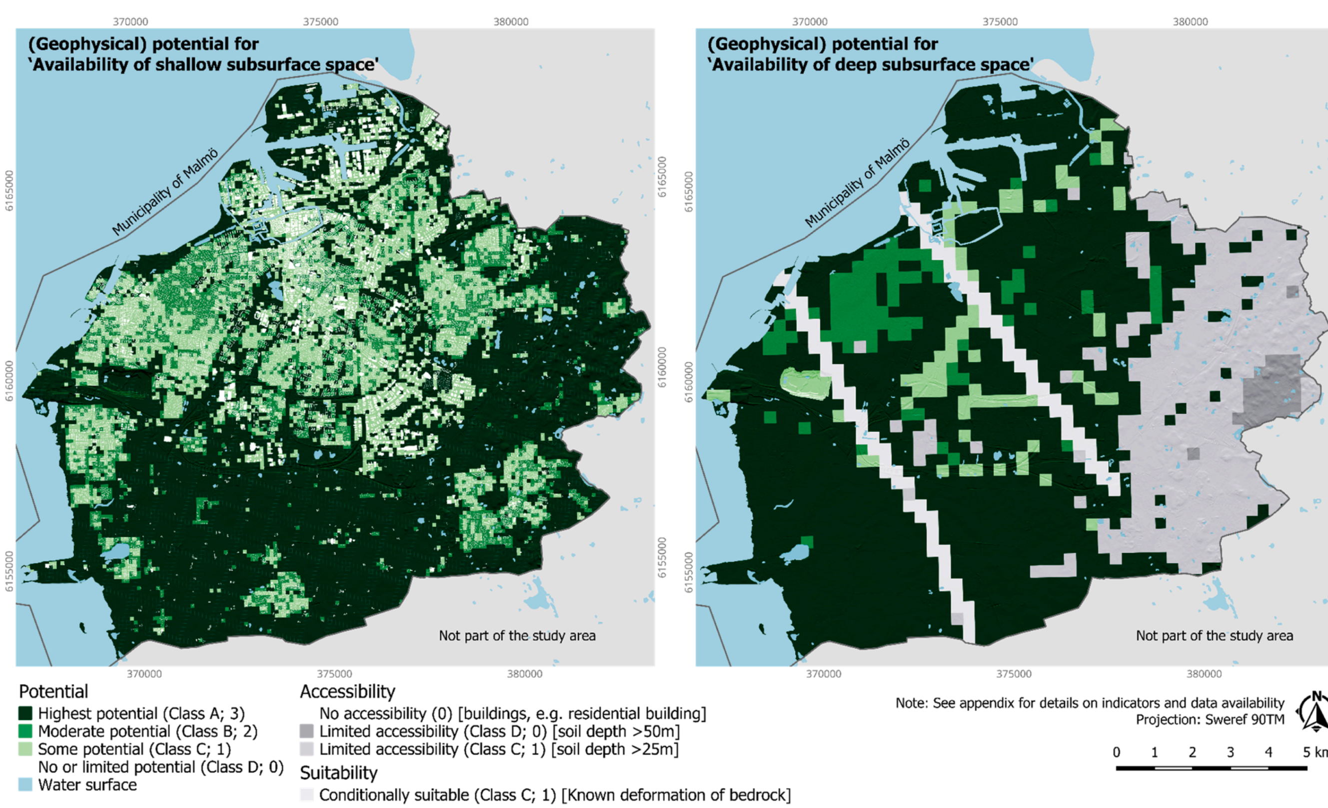

Fig. 7. Baseline maps of the potential for Availability of shallow subsurface space (left) and Availability of deep subsurface space (right).
Note: See SM for indicators used.

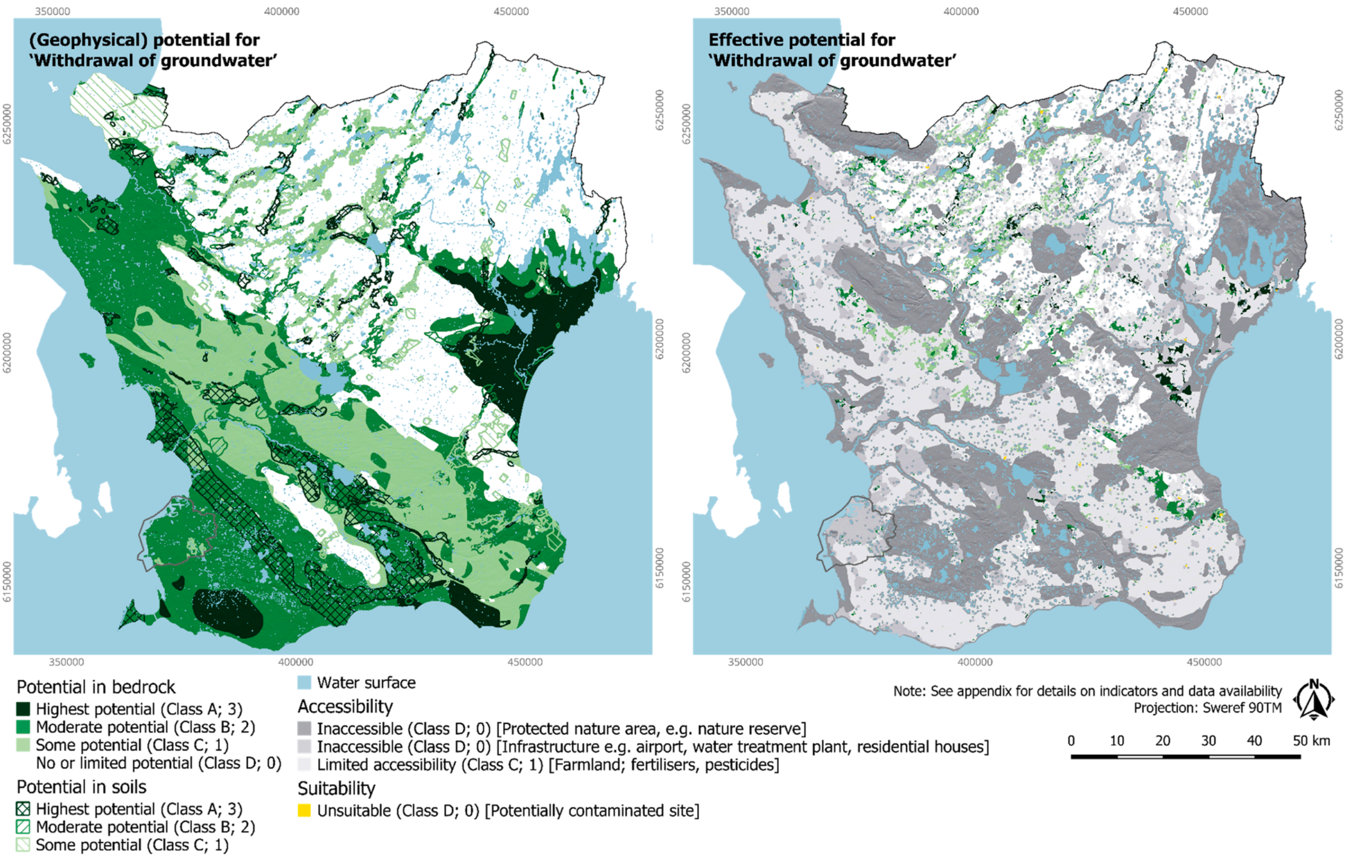

Fig. 8. Baseline map of the potential for Withdrawal of groundwater (left) and map showing the effective potential (right).
Note: See SM for indicators used.

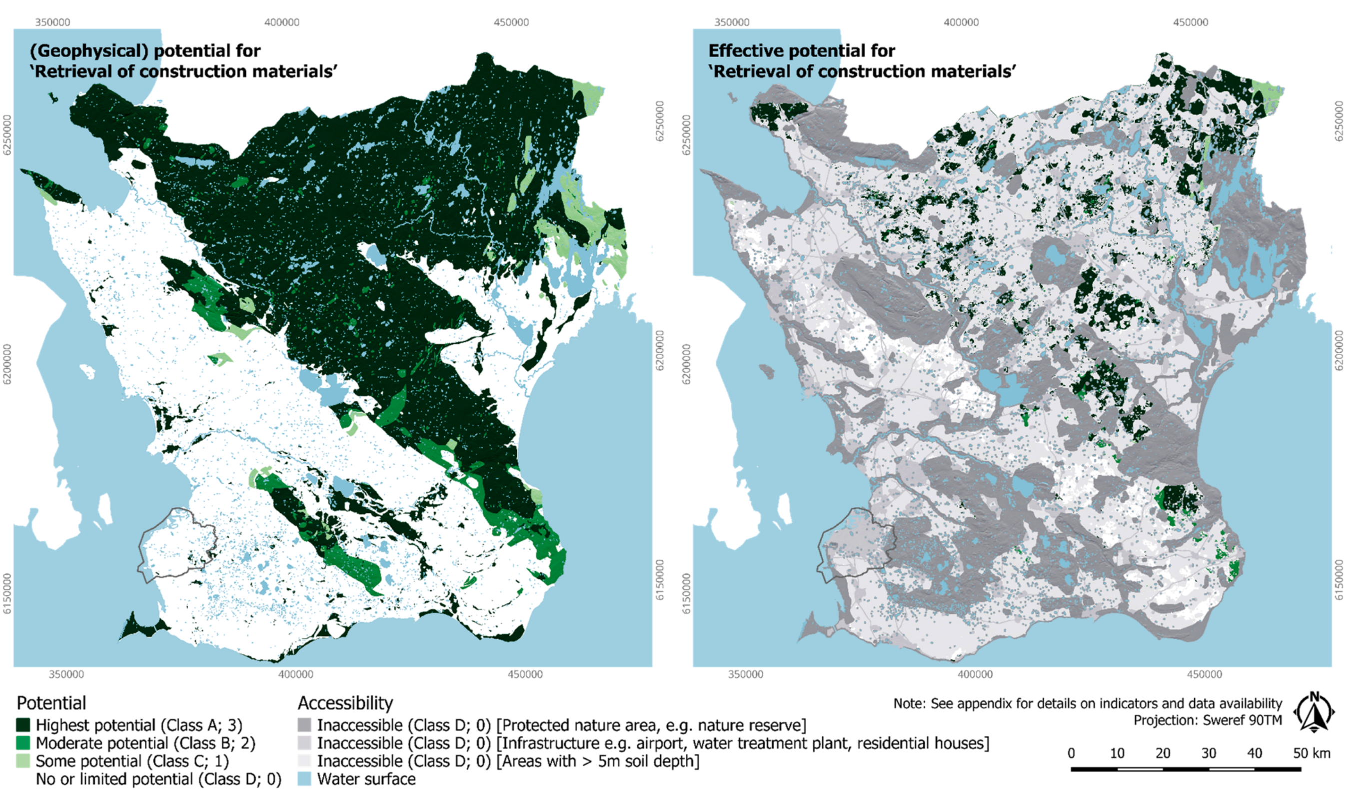

Fig. 9. Baseline map of the potential for Retrieval of construction materials (left) and map showing the effective potential (right).
Note: See SM for indicators used.

potential (Class C), 5 % fall into the moderate class (Class B), and 29 % into the highest class (Class A). Although the classification is relative, and the limestone and sandstones in the study area are expected to have thermal conductivity at the lower end, the relatively good hydraulic conductivity associated with the Limhamn Member (found in the central and northern parts of the city) raises the potential for BTES systems. Further, recent 3D modelling of the bedrock beneath the city (Erlström et al., 2023) indicates that this member is relatively prominent in the area and can be readily accessed through drilling. Notably, the highest class (Class A) is also intersected by two major faults in the study area, which cross the municipality from north-northwest to south-southeast, potentially increasing the potential further.

In terms of effective potential, most of it is readily accessible, with only some competition for subsurface space in the central parts of the city, and soil thickness becoming an issue only in the easternmost parts of the municipality. Since boreholes and heat–cold exchangers generally require little space and can, in principle, be drilled through most surface areas, surface space is not considered a limiting factor, although buildings themselves are treated as unavailable space.

4.2.3. Potential for infiltration and retention of stormwater

Fig. 6 presents the baseline map for the potential to infiltrate and retain stormwater and the effective potential. For details on indicators and classes used, see SM. The map is based on three parameters included in the indicator: soil lithology, where coarser-grained soils are assumed to have higher infiltration potential; soil depth, which must be sufficient to support infiltration; and groundwater level, where a minimum unsaturated zone thickness is required. Specifically, a combined soil and unsaturated zone depth of at least 1 m is assumed necessary for effective infiltration. The map identifies areas within the municipality with greater potential for stormwater infiltration and retention, thereby reducing peak discharge into adjacent watercourses.

Approximately 78 % of the municipality is classified as having some potential (Class C), while 17 % falls into the moderate category (Class B) and 5 % into the highest category (Class A), with higher-potential areas concentrated in the south-eastern part of the municipality. The potential to infiltrate and retain stormwater is limited by the widespread presence of shallow glacial till, anthropogenic filling material, and postglacial coastal sediments, which either exhibit low vertical permeability or offer limited storage capacity, reducing their potential for infiltration-based solutions. It should be noted that the vertical infiltration properties of filling materials in the study area are poorly constrained and were estimated to be moderate based on field observations.

When considering effective potential, the share of theoretical potential that can realistically be utilised, additional limitations become evident. Most of the inherent capacity for stormwater infiltration is severely restricted by impermeable surfaces associated with dense urban development. Furthermore, the presence of contaminated sites poses a significant barrier, as infiltration in these areas risks mobilising pollutants.

4.2.4. Potential for availability of shallow and deep subsurface space

Fig. 7 presents the baseline geosystem services potential map for Availability of shallow subsurface space[4] and Availability of deep subsurface space (see SM for the indicators applied). These maps represent the availability of subsurface space, where higher potential indicates greater availability. The analysis distinguishes between shallow subsurface space (<10 m in depth) and deep subsurface space (deeper than 10 m). In this study, shallow subsurface space and deep subsurface space are treated as two distinct specific geosystem services. Shallow subsurface space refers to the uppermost part of the subsurface (depth <10 m), where competition with surface-level land use, building foundations, tree roots, and utilities is most pronounced. In contrast, deep subsurface space refers to depths >10 m, where conflicts are driven primarily by subsurface infrastructure, geological constraints, and technical feasibility. The separation is important because these two domains serve different functions, face different accessibility limitations, and support different types of climate-related adaptation measures.

Shallow subsurface space is assessed using a metric that accounts for surface building density, calculated by summing the number of buildings per $100 m^2$. This metric serves as a proxy for the degree of competition for subsurface space near the surface, where areas with lower density offer more flexibility and reduced risk of conflicts. Approximately 24 % of the municipality is classified as having some potential (Class C), 14 % falls into the moderate category (Class B), and 62 % into the highest potential class (Class A). As expected, the spatial distribution of these classes reveals that higher-potential areas are predominantly located outside the city centre, where building density is lower and subsurface access is less restricted.

For deep subsurface space, defined as depths exceeding 10 m, the absence of major subsurface infrastructure, such as regional utility networks, road tunnels, and railway tunnels, is used as a proxy for availability. That said, it should be noted that, due to the confidential nature of certain subsurface constructions, the maps have been deliberately designed to omit sensitive details, which significantly influences the outcome of the analysis. Regarding the effective potential for deep subsurface space, areas with thin rock cover present additional challenges. Here, the inverse of soil depth is used as an indicator of thin rock cover, with depths greater than 25 m classified as having limited accessibility and those exceeding 50 m considered inaccessible. In such conditions, the underlying bedrock may lack sufficient horizontal support to counter vertical loads, necessitating additional reinforcement. This requirement can substantially increase construction costs and raise safety concerns. However, please note that the depth at which these issues become critical depends on the type of installation and specific design choices; therefore, depth thresholds may need to be adjusted accordingly.

In addition to the indicator used in this study, recent work has explored the development of quantitative geophysical proxy indicators for urban subsurface space use, which may offer valuable approaches for mapping and assessing deep subsurface space. For example, Alofe et al. (2026) proposed geophysical proxies, based on airborne magnetic data, to indicate subsurface structures. Such proxies offer promising opportunities for improving the mapping and evaluation of deep subsurface space, where direct observation and data availability are often limited; however, they were not available for the study setting at the time of writing.

4.2.5. Potential for withdrawal of groundwater

Fig. 8 presents the baseline map for the potential to extract groundwater and the effective potential.[5] For details on indicators and classes used, see SM. The map is based on estimates of water withdrawal rates (Hjerne et al., 2021a, 2021b) from aquifers in the Scania region. Estimates on the withdrawal capacity of groundwater aquifers are divided into two types of aquifers: i) large, mainly glaciofluvial deposits and parts of the sedimentary bedrock, and ii) small, mainly till,

[4] Please note that subsurface space and underground space can represent distinct concepts depending on the context. In the context of this paper, we follow the distinction outlined by Peng et al. (2021), where ‘subsurface space’ refers to the broader physical domain beneath the surface, encompassing both natural and engineered environments. In contrast, ‘underground space’ typically denotes engineered or planned spaces created for human use, such as tunnels, basements, or utility corridors.

[5] Please note that only the withdrawal rates are included in the potential here; the recharge capacity is not included in the indicator. That said, recharge into local aquifers along the western Swedish coast is generally quite favourable, owing to the region’s relatively wet climate (Eveborn et al., 2017).

Table 4
Overview of the sensitivity analysis for the developed maps.

Map	NA-RMSE	MDI	Scenarios tested	Most sensitive parameter(s)
Regulation of coastal erosion	0.10	0.16	17 scenarios: lithology and sea-level-rise (SLR) variants	Filling material classification (−1 more impactful than +1; RMSE up to 0.86) and sea-level-rise envelope (No SLR 0.77; +5 m 0.61; +4 m 0.47).
Retrieval of heat and cold from the subsurface	0.22	0.22	6 scenarios: inclusion of fault and bedrock lithology variants	Copenhagen Member reclassification by ±1 (RMSE 0.83 in both directions) and Limhamn Member downgrade (RMSE 0.52).
Infiltration and retention of stormwater	0.33	0.21	25 scenarios: unsaturated zone depth, soil depth and soil lithology variants	Deepening the unsaturated zone (+4 m RMSE 1.34; +2 m 0.56) and upgrading filling material by +1 (RMSE 1.28); most lithologies are also high and symmetric (≈0.65–0.85).
Availability of shallow subsurface space	0.21	0.24	6 scenarios: density threshold variants	Changes to threshold for activities that are assumed to require more subsurface space (e.g. larger industries)
Withdrawal of groundwater	0.08	0.10	4 scenarios: capacity threshold variants	Generally low influence, but Low-end capacity boundary near 500 m^3/d (RMSE 0.45) is the most significant
Retrieval of construction materials	0.20	0.21	4 scenarios: changes to the capacity related to gravel and parent-rock (crushed bedrock) criteria relaxed	Gravel downgrades show near-linear increases in deviation (0.29 → 0.57 → 0.86), and relaxing parent-rock criteria produces a large system-wide shift (RMSE 0.73)

Note: See SM for details.

Table 5
Overview of datasets used for validation of the maps.

	Specific geosystem service					
	Regulation of coastal erosion	Retrieval of heat and cold from the subsurface	Infiltration and retention of stormwater	Availability of deep and shallow subsurface space	Withdrawal of groundwater	Retrieval of construction materials
Independent proxy data used for validation (dataset)	Constructed erosion controls (Lantmäteriet, 2025)	Geoenergy wells (SGU, 2024)	Areas prone to flooding (Malmö stad, 2016).	*No independent dataset found.*	Water protection area	Active quarries (Eilu, 2012; Schoning & Mortensen, 2021)
Reasoning why the potential should fit with the independent proxy	Erosion controls, such as groins, coincide with low erosion regulation.	Geoenergy wells coincide with demand and potential for retrieval.	Low frequency coincides with high flood regulation.	*No independent dataset found.*	Water protection areas coincide with demand and potential for withdrawal.	Active quarries coincide with demand and potential for supply.

Note: No independent dataset was identified for the provisioning of shallow and deep subsurface space. This is mainly due to that information on subsurface installations is confidential.

fine-grained soils or crystalline bedrock. The smaller aquifers have a relatively limited capacity due to their limited volumetric extent and/or effective porosity, and as such, these are mostly relevant for individual households' water supply.[6] In this study, the focus is on the larger aquifers that relate to communal or municipal drinking sources.

The map covers the Scania region rather than being limited to Malmö municipality, as aquifers frequently extend beyond administrative boundaries. Groundwater availability in Malmö may therefore be significantly influenced by recharge zones, geological formations, and land-use patterns located elsewhere in the region. Broadly, the map indicates a relatively good potential for groundwater withdrawal across the region (noting that water quality was not included in the analysis and is generally less critical for process water applications). However, it also highlights that a substantial share of this potential is either inaccessible, such as areas restricted by protected natural zones, or unsuitable due to conflicting land uses, including airports and cemeteries.

Approximately 19 % of the region is classified as having some potential (Class C), 28 % falls into the moderate class (Class B), and 15 % into the highest class (Class A). The remaining 39 % is classified as having no or limited potential for larger groundwater wells. Higher-potential areas are primarily concentrated in the south-western part of the region, where sedimentary bedrock dominates, as well as in unconsolidated glaciofluvial formations such as eskers and deltas. However, when considering effective potential, the share of theoretical potential that can realistically be utilised, significant constraints emerge. Almost all opportunities for groundwater withdrawal are limited by competing land and subsurface uses. The most restrictive factor, in terms of area, is agricultural land, where the use of pesticides and fertilisers is common, potentially degrading water quality (although this may be less problematic for process water applications). In addition, such land may be excluded from drinking water supply projects to prioritise food production. Protected areas, such as nature reserves, represent the second most significant constraint, as environmental regulations strictly limit interventions that could disrupt ecosystems or alter hydrological regimes. Consequently, while the theoretical potential appears substantial in certain geological zones, the actual scope for implementation is considerably narrower, underscoring the importance of integrating hydrogeological assessments with land-use planning and regulatory frameworks.

4.2.6. Potential for retrieval of construction materials

Fig. 9 presents the baseline map for the potential to extract geomaterials and the effective potential. For details on indicators and classes used, please refer to SM. The map was created by connecting information about rock properties to lithological units (see Schoning & Mortensen, 2021) and known till and gravel deposits to produce a map indicating the potential for retrieving various geomaterials suitable for concrete production and/or as a filling material.

The map encompasses the Scania region and highlights areas with potential for construction material supply, including glaciofluvial deposits, till materials, and crushed crystalline bedrock, where higher potential values indicate greater estimated extractable volumes. The assessment is made for the Scania region, as it is unrealistic to expect a sufficient supply of geomaterials within the city boundaries. Nonetheless, minimising transport distances for materials has notable economic (e.g. cheaper), societal (e.g. aspects of justice), and environmental (e.g. lower CO_2 emissions) benefits. A regional-scale map also facilitates comparative analysis across different areas, enabling the identification

[6] Defined in the European Drinking Water Directive as <10 m^3/d or serves <50 people.

of zones with high potential, regional constraints, and opportunities for coordinated resource management.

For gravel and moraine deposits, a greater soil depth is advantageous as it provides more material. Conversely, using crystalline rock necessitates the removal of the overlying soil to access the underlying rock. Initiating quarrying operations when the soil depth exceeds five metres becomes economically challenging, even if the underlying rock possesses favourable properties (Schoning & Mortensen, 2021). Approximately 2 % of the Scania region is classified as having some potential (Class C), while 4 % falls into the moderate category (Class B) and 47 % into the highest category (Class A), with higher-potential areas concentrated in the north-eastern part of the region, where crystalline rock becomes more prominent than the sedimentary rocks that dominate the south. The remaining 47 % are classified as having no or limited potential (Class D).

When considering effective potential, the share of theoretical potential that can realistically be utilised, significant constraints emerge. Much of the identified potential lies within protected areas or in close proximity to urban centres, making it unlikely that the necessary mining permits would be granted. Environmental protection regulations and land-use priorities often take precedence, particularly in areas designated for biodiversity conservation or recreational purposes. It is, however, noteworthy that there are active quarries currently operating in zones classified as inaccessible or unsuitable in Fig. 9. A possible explanation is that the initial permits for these quarries were issued several decades ago, under regulatory frameworks that were less stringent than those in place today.

4.3. Sensitivity analysis and validation

4.3.1. Sensitivity analysis

Table 4 summarises the results from the sensitivity analysis. Across all six maps, internal disagreement remains uniformly low to moderate on the 0 to 1 scale (MDI ≈ 0.10–0.24), which indicates that even when input parameters are changed, the resulting maps retain a broadly consistent spatial pattern. However, overall sensitivity, expressed as the range-normalised average deviation (NA-RMSE), varies considerably between services. The Withdrawal of groundwater exhibits the lowest sensitivity (NA-RMSE ≈ 0.08, MDI ≈ 0.10), followed by Regulation of coastal erosion (≈ 0.10, 0.16). Moderate sensitivity is observed for Retrieval of construction material (≈ 0.20, 0.21), Availability of shallow subsurface space (≈ 0.21, 0.24), and Retrieval of heat and cold from geoenergy systems (≈ 0.22, 0.22). The highest sensitivity is associated with Infiltration and retention of stormwater (≈ 0.33, 0.21), where parameter changes produce the most pronounced deviations from the reference map.

In most services, the average pairwise difference across all maps (AP-RMSE) exceeds the mean deviation from the reference, which signals that the spread is driven by a small number of high-leverage assumptions rather than by many small, cumulative changes. The only exception is stormwater infiltration, where AP-RMSE is approximately equal to the mean (i.e. mean deviation from the reference map, which is the average RMSE between each scenario map and the reference map), indicating that sensitivity is broadly shared across scenarios once the dominant parameters are changed.

The most sensitive scenarios for each map reveal where the uncertainty is concentrated. For Regulation of coastal erosion, the largest deviations occur when the capacity of anthropogenic filling material is classified as having some potential rather than moderate potential to infiltrate stormwater (RMSE ≈ 0.86) and when sea-level rise assumptions are altered, particularly the scenario with no sea-level rise (RMSE ≈ 0.77). These changes substantially reshape the coastal erosion capacity, underscoring the importance of assumptions about anthropogenic filling and future water levels. In the case of Retrieval of geoenergy, the lithological unit the Copenhagen Member exerts the strongest influence, with $a \pm 1$ class change producing RMSE values of about 0.83 in both directions, while downgrading the Limhamn Member also has a substantial effect (RMSE ≈ 0.52). For stormwater infiltration and retention, the largest deviations occur when an unsaturated zone thickness of 5 m is required (RMSE ≈ 1.34) and when the filling material is classified as having the highest rather than moderate infiltration potential (RMSE ≈ 1.28), both of which shift extensive areas into different capacity classes. The map for shallow subsurface space availability is generally robust, but altering the classification rule for industry-intensive areas, tightening the threshold to more than three such buildings per 100 × 100 m, produces the greatest change (RMSE ≈ 0.75), far exceeding the effect of adjusting general building-density thresholds. Withdrawal of groundwater is the least sensitive overall, yet lowering the low-end capacity threshold to 500 m^3/d results in the highest deviation for this service (RMSE ≈ 0.45), whereas pushing it further down to 100 m^3/d has no effect. Finally, for Retrieval of construction material, the strongest responses occur when gravel is downgraded by three classes (RMSE ≈ 0.86) and when the technical criteria for parent rock are relaxed, increasing its capacity by one class (RMSE ≈ 0.73), both of which significantly alter the spatial distribution of high-potential zones.

4.3.2. Validation

The independent datasets used for validation are presented in Table 5. Further details on the datasets and validation results are available in the SM. Note that the validation analysis focuses on geosystem service potential (i.e. not on effective potential), and that the independent datasets used for validation encompass both supply and demand, such as the distribution of geoenergy wells, locations of active quarries, and water protection areas. These datasets, used solely for validation and not as mapping inputs, reflect both natural potential and external factors like policy, economics, and demand; thus, their spatial distribution may not directly correspond to geophysical suitability. Consequently, spatial overlap between the mapped potential and these features should be interpreted as indicative rather than definitive evidence of map validity. Moreover, no independent dataset was available for the specific services of subsurface space availability, either for shallow or deep subsurface space. The lack of independent datasets related to the availability of subsurface space is primarily because information on subsurface installations is confidential.

4.3.2.1. Regulation of coastal erosion. To validate the map for Regulation of coastal erosion, we compared the developed map with the distribution of hard erosion control structures such as groynes, breakwaters, seawalls, and retaining walls. Approximately 25 % of the coastline lacks such measures, while the remaining 75 % is protected by these structures. Among unprotected sections, 70 % were classified as having some potential (Class C) and 30 % as moderate potential (Class B). In contrast, protected coastlines were predominantly classified as moderate potential (Class B), with some harbour areas falling into the highest class (Class A). This outcome was contrary to our initial expectation that engineered defences would coincide with areas of lowest natural erosion regulation capacity. Notably, many protected areas with moderate or high mapped potential consist of artificial filling material, which may have led to an overestimation of their resistance to erosion, or may reflect engineering standards, safety requirements, or land reclamation activities rather than natural conditions. We intentionally retained this validation approach to highlight two important points: first, the urgent need for more robust indicators and datasets that can reliably distinguish between natural potential and engineering demand; and second, to transparently present an example of a validation method that does not work as intended to encourage further methodological development.

4.3.2.2. Retrieval of heat and cold from the subsurface. To validate the map Retrieval of heat and cold from the subsurface, the developed map

Table 6
Overview of the results from the workshop.

Map	Perceived usability	Suggested improvements	Refinements made
Regulation of coastal erosion	Limited engagement	No suggestion given	The maps were redesigned to highlight areas that are at risk of flooding due to rising sea levels
Retrieval of heat and cold from the subsurface	Useful for future planning discussions regarding Borehole Thermal Energy Storage (BTES)	Feedback on the map emphasised that a higher resolution is needed for the maps to be useful	The maps were redesigned to highlight relative differences between the rock units. Accessibility and suitability were separated, more clearly constrained and colour-coded
Infiltration and retention of stormwater	Useful for initiating dialogue when designing green corridors and blue-green infrastructure. The map could be used as a complement to existing planning tools	Feedback on the map emphasised the importance of distinguishing between accessibility and suitability, and also to provide quantitative data—such as estimates of stormwater infiltration capacity in m^3 per hour—to supplement the qualitative information	Accessibility and suitability were separated, more clearly constrained and colour-coded
Availability of deep and shallow subsurface space	Useful for initiating dialogue on the constrained availability of subsurface space	Feedback on the map emphasised that higher resolution is needed for the maps to be useful and that sea-level rise risks should be included in these maps	A finer grid was used to enhance resolution. Accessibility and suitability were separated, more clearly constrained and colour-coded
Withdrawal of groundwater	The map was considered useful for discussion	Feedback on the map emphasised the importance of distinguishing between accessibility and suitability, and of accounting for regulatory constraints on water withdrawal	Accessibility and suitability were separated, more clearly constrained and colour-coded
Retrieval of construction materials	Useful for initiating dialogue on how to ensure the city's needs for construction materials and where they stem from	Mapping and quantification of anthropogenic soils (for use the in e.g. recycling depots)	Accessibility and suitability were separated, more clearly constrained and colour-coded

Note: See detailed feedback, the maps shown and other materials related to the workshop in the SM.

layer was compared with reported geoenergy wells in Malmö. A total of 2216 geoenergy wells have been documented in the municipality. Of these, 47 % are shallower than 60 m, 16 % range between 60 m and 100 m, 6 % between 100 m and 200 m, and 32 % exceed depths of 200 m. Among the wells shallower than 60 m, 60 % are located within the highest potential class (Class A), 5 % within the moderate potential class (Class B), 36 % within the some potential category (Class C), and 0 % fall within the no or limited potential class (Class D). Assuming that a higher density of geoenergy wells corresponds to greater potential, the spatial patterns depicted in the map broadly support this hypothesis.

4.3.2.3. Infiltration and retention of stormwater. To validate the map Infiltration and retention of stormwater, the developed map layer overlapped with areas that were identified as prone to flooding in Malmö stad (2016). The majority of flooding-prone areas fall within the some potential class (Class C), accounting for 78 % of the observed flooding affecting buildings and roads. The remaining 22 % occurred in the moderate potential class (Class B). Given the hypothesis that a high frequency of flooding corresponds with low flood regulation capacity, the spatial patterns shown in the maps support this assumption. However, it is important to note that many flood-prone areas are located along culverted former ditches and streams, as well as along the Riseberga river, which flows along the city's eastern boundary (Malmö stad, 2016). These hydrological features may exert a stronger influence on flood risk than surface infiltration capacity alone. Furthermore, the risk of flooding can also be influenced by the building's own design and infrastructure. For instance, if the property lacks backwater valves—devices that prevent sewage or stormwater from flowing back into the building during heavy rainfall—water can enter through drains and cause interior damage. This means that even in areas with adequate external drainage, the absence of such protective measures can leave a building vulnerable to flooding.

4.3.2.4. Withdrawal of groundwater. For validation purposes, the developed map was compared with water protection areas in the region. Of these areas, 29 % overlap with zones identified as having the highest potential for groundwater withdrawal (Class A), 39 % fall within the moderate potential category (Class B), and 6 % within the category indicating some potential (Class C). The remaining 25 % overlap with areas classified as Class D, which represents zones with limited or uncertain potential. Thus, the majority of water protection areas are located within the highest (Class A) and moderate (Class B) categories, together accounting for 68 %. If the underlying assumption is that water protection areas can serve as a means of validating the potential maps, this suggests that the developed maps are, overall, relatively accurate.

The 25 % of water protection areas that fall within Class D can possibly be explained by the fact that these areas also include surface water. Additionally, some individual water protection areas are relatively large and span multiple classes. For example, a water protection area may predominantly fall within the highest class (Class A) but also extend into an area classified as Class D. Such a larger area may have been designated as a water protection zone to safeguard against contamination.

4.3.2.5. Retrieval of construction materials. For validation, the developed map was compared with the locations of existing quarries. The majority of quarries are situated in areas identified as having a high potential for construction material supply (Class A), accounting for 72 %. A further 26 % are located within the moderate potential category (Class B), while 2 % fall within the class representing no or limited potential (Class D). Assuming that existing quarries can serve as a proxy for validating the maps, the observed spatial patterns broadly support the accuracy of the developed maps. The one quarry that is located within Class D, extracts chalk as an industrial mineral for e.g. cement production.

4.4. Feedback on the developed geosystem service potential maps

The initial workshop with the city of Malmö provided a comprehensive overview of various geosystem (and ecosystem) services currently utilised in Malmö to support climate resilience, illustrating how the subsurface can help mitigate climate-induced risks and enhance resilience (see examples and details in the SM). The subsequent workshop with municipal civil servants offered valuable insights into how the developed geosystem service maps were perceived in terms of their usefulness and applicability across various planning contexts. While some maps elicited limited or no comments, others prompted detailed responses, particularly regarding their potential integration into climate resilience and urban planning strategies. Overall, the maps were considered useful tools for initiating discussion and supporting more informed and sustainable planning decisions. However, concerns were raised regarding resolution, clarity, and the inclusion of contextual data. In response to this feedback, the maps were refined as far as possible in line with the suggestions received. For those maps that received little or no direct feedback, refinements were instead guided by general feedback and by insights gained from participant discussions about the other maps. Table 6 outlines both the participants' comments and the corresponding adjustments made. The maps presented during the session are shown in SM.

Engagement with the potential for Regulation of coastal erosion map was limited, which may suggest a perceived lack of relevance, unfamiliarity with its practical application, or that participants were already aware of the issue and felt the map offered little new information. Similarly, the potential for Retrieval of construction materials map generated few, albeit constructive, remarks. These remarks included suggestions to map anthropogenic soils (i.e. filling material in the city) and to use the map to support the establishment of recycling depots for excavated soil.

The potential for Retrieval of heat and cold from the subsurface map attracted greater attention and was recognised for its potential to inform future planning discussions, particularly in relation to extracting cold as a countermeasure to heatwaves. Although municipalities are not responsible for planning small-scale private heating or cooling systems, as these decisions rest with individual property owners, the map could nonetheless serve as a catalyst for dialogue on the feasibility of such systems in response to climate change. The potential for large-scale BTES systems was also discussed. It was further noted that areas likely to experience heat-related challenges in a warmer climate are often situated in or near zones with higher geoenergy potential. That said, concerns were also raised regarding the "first-come, first-served" principle governing subsurface resource allocation, as well as the environmental implications of active cooling technologies.

The most comprehensive feedback was provided for the map on the potential for Infiltration and retention of stormwater. Planners highlighted its potential application in designing green corridors and blue-green infrastructure, such as roadside ditches and floodable road sections. The map was viewed as a valuable complement to existing planning tools, including the green space factor and water coefficients. However, participants called for higher-resolution data, the inclusion of current groundwater levels, and clearer distinctions between accessible and suitable areas (e.g. contaminated or paved surfaces). Quantitative data, such as estimates of stormwater infiltration capacity in m^3 per hour, were also requested to supplement the qualitative information currently provided. The map concerning the potential for Withdrawal of groundwater was considered useful as a basis for discussion, although current planning efforts primarily focus on contamination prevention rather than groundwater supply. Feedback on these maps emphasised the importance of distinguishing between accessibility and suitability.

The maps on the potentials for Availability of deep and shallow subsurface space also received attention, especially in regard to spatial limitations and the allocation of subsurface space for infrastructure, tree roots, and shelters. However, the map depicting shallow subsurface space potential was criticised for offering limited planning value due to its uniform representation across central areas and its omission of sea-level rise risks. Despite these limitations, both maps (Availability of shallow and deep subsurface space) were seen as useful for initiating dialogue on the constrained availability of subsurface space

5. Discussion

5.1. Methodology – benefits and limitations

In this paper, we present a methodology to create maps displaying the potential for geosystem services and an evaluation of their usability, tested with city servants from the Malmö municipality. The methodology is adapted from similar work on ecosystem services (Andersson-Sköld et al., 2018; Baró et al., 2016) but was modified to better suit geosystem services. The methodology is intended to be straightforward to apply to create maps that can be used in planning processes, environmental impact assessments (EIA), and other cases where understanding how the geophysical environment can provide services of importance. In the case of this study, it is for climate adaptation. To ensure practicality, the supply of a given service (i.e., the physical environment), including aspects such as accessibility and suitability, is separated from demand (i.e., the social and economic system). This distinction is made to account for the fact that perceptions of benefits and values can change over time. For example, due to increasing demand for climate change adaptation or policy shifts that alter the (perceived) importance of a service. This argument, that separating supply from demand enhances practicality, has also been made in the context of ecosystem services (see e.g. Andersson-Sköld et al., 2018; Baró et al., 2016).

The methodology proved to be applicable and easy to use for the study site. However, it also emphasises the lack of information related to geosystem services. Although some of the services labelled in this study as geosystem services are included in the various ecosystem services assessments and framework (see e.g. the geophysical section in CICES v5.2), there is a scarcity of information on how these geosystem services should be indicated and mapped (Lundin-Frisk et al., 2025). A substantial part, and part of the novelty, of this study has therefore been to refine and adapt the indicators suggested in Lundin-Frisk et al. (2025) to the study setting and to proceed from a theoretical discussion towards an operationalisation of geosystem services indicators. Given this, there is a dire need for more studies on the mapping of geosystem services, either expanding on the indicators suggested here or offering novel ways of mapping these services.

While ecosystem service and geosystem service mapping have much in common, it should also be noted that for maps related to construction-oriented geosystem services, such as the 'subsurface space availability' and the 'regulation of temperature by the subsurface', accessibility is influenced not only by spatial constraints or competing land uses, but also by the design of the construction itself and the technologies employed. For instance, advancements in drilling techniques have made it economically viable to construct deeper geoenergy wells. Simultaneously, stricter environmental regulations and safety standards have introduced new requirements for facilities and construction methods. Consequently, the accessibility and suitability assessments presented in this study should be regarded as snapshots, reflecting current conditions in society, such as technology, policy and law.

Similar to the work of ecosystem services (Andersson-Sköld et al., 2018; Baró et al., 2016) the methodology proposed here should be complemented by the final two steps of the cascade model, which represent demand and values. Incorporating demand is essential for assessing current and future trends, as well as for identifying which services are considered most critical by stakeholders. This step provides insight into societal priorities and helps to align resource management with actual needs. Valuation, on the other hand, is important because it translates the geophysical supply of services into socio-economic terms, enabling comparison across different services and supporting informed decision-making. That said, valuation of nature is intricate. For example, economic valuation has been described as inherently complex (Tinch et al., 2019), ethically contested (Hausman et al., 2016; Spangenberg & Settele, 2016), and potentially counterproductive for conservation (Gómez-Baggethun & Ruiz-Pérez, 2011). However, it remains an unavoidable aspect of decision-making. Valuation, whether explicit or implicit, occurs whenever decisions are made by policymakers, agencies, businesses, or individuals. In practice, decisions are often based on financial metrics associated with natural resources. Such metrics, however, fail to capture all diverse values associated with nature (e.g. IPBES, 2022). Explicit spatial mapping and subsequent valuation of ecosystem and geosystem services could therefore enhance transparency and support more informed trade-offs, and thus, contribute to well-informed climate resilience planning and a more sustainable use of the multiple resources provided by the subsurface.

Clearly, developing geosystem services maps is no less challenging than creating ecosystem service maps. However, developing geosystem service maps poses a set of slightly different challenges than ecosystem service maps. These mostly relate to a lack of studies on geosystem services, issues with confidential information and dependency on technology that is rapidly advancing. Furthermore, the classification logic and indicator selection, while grounded in literature and expert input, also warrant further scrutiny. For instance, the thresholds used to define "high potential" areas will not translate across municipalities with different geological contexts or data availability. That said, some challenges are also shared; data availability and quality are persistent issues, the need for proxies or models due to limited direct measurement and defining and categorising the services consistently.

5.2. Geosystem services potential in Malmö

The geosystem service maps produced for Malmö render the subsurface visible and easier to account for planning by translating geophysical environments into capacity classes (i.e. an indication of how much a specific geophysical environment can contribute to providing a geosystem service) and, where relevant, overlaying accessibility and suitability constraints. Together, these show that the city exhibits a broad latent potential to draw on geosystem services that matter for climate adaptation, but that this potential is highly uneven across space and frequently curtailed by land use, contamination risks, and technical or legal limitations.

Across the four climate adaptation themes used by Malmö, rising sea levels, heavy rains, heat, and drought, the mapping identifies distinct yet interlinked geosystem services. Most of Malmö's coastline exhibits good to exceptional inherent potential to resist erosion, but a notable stretch of the northern waterfront has low potential and coincides with low-lying, densely developed areas where breakwaters already exist, and further protection is likely to be required as the mean sea level rises. Because "hard" protection demands large volumes of aggregates, the erosion map must be read together with the map for construction materials: this juxtaposition reveals that immediate, local supply is limited once suitability and accessibility are accounted for, pushing viable prospects to the central–northeastern parts of the county. This linkage is an explicit result of the mapping: erosion resilience should be planned together with regional aggregate supply in order to avoid shifting risks through longer transport chains, higher emissions, and added costs.

For heavy rains, the maps emphasise the potential for infiltration and retention of stormwater and the strategic use of subsurface space. Large parts of Malmö present an inherent potential to infiltrate runoff where soils are permeable; however, this potential is often inaccessible in practice in the most flood-prone urban districts because of extensive impervious cover and the prevalence of anthropogenic filling material of uncertain permeability and with contamination risks. The mapping, therefore, distinguishes between potential and accessibility/suitability, clarifying where converting selected impervious surfaces to green infrastructure could unlock latent potential. In parallel, the map of subsurface space identifies where subsurface conditions and current space use allow for stormwater conveyance or storage facilities (e.g., large drainage tunnels), while also signalling potential conflicts with existing utilities and the need to consider the generation and reuse of surplus excavation masses. In dense districts, high demand for subsurface space coexists with constrained suitability, implying that the most ambitious conveyance options will require careful sequencing and co-location strategies to avoid crowding out future uses.

Under heat stress conditions, the mapping links three key services: water quantity regulation (through infiltration that enables evapotranspiration cooling), regulation of subsurface temperature via the possibility for cooling by retrieving cold from the subsurface, and the availability of subsurface space to provide "cool refuges". While the prevalent limestones in the Malmö subsurface are generally characterised by relatively low thermal conductivity, some areas exhibit higher relative potential. The presence of a substantial number of geoenergy wells in these areas highlights that, at the building-to-block scale, geoenergy remains a viable option, and the map helps anticipate where performance and costs may diverge from average conditions. However, relatively low thermal conductivity could constrain system performance at larger scales. The Retrieval of heat and cold from the subsurface (geoenergy) potential is also generally good, with only a few concerns: thicker soil cover in the eastern municipality increases drilling costs, and the densely populated central parts of the city raise the likelihood of spatial conflicts with other subsurface installations. Notably, when geoenergy is considered alongside the infiltration maps, a systemic picture emerges: the same districts that face the highest heat risks often possess inherent infiltration capacity that is currently inaccessible under existing land use. Reclaiming this potential would simultaneously reduce peak flows during cloudbursts and enhance summertime evaporative cooling, delivering dual mitigation benefits. When combined with geoenergy wells, this approach could further enhance the multifunctional use of subsurface resources and mitigate climate-induced risks.

Three services were identified in the context of drought resilience: regulation of water quantity, subsurface space for storage, and the provision of groundwater. At the regional scale, groundwater resources are generally robust; however, the maps clearly show that the potential becomes more constrained closer to Malmö due to less favourable hydrogeological conditions, and to limitations in suitability arising from contamination risks and inaccessibility caused by competing land uses. That said, there is still potential for additional use of groundwater at the outskirts of the city, for example, as an additional groundwater reserve.

While the developed maps indicate that multiple services should be considered in the context of climate resilience, the list is not exhaustive. Incorporating additional services could further strengthen assessment and planning processes. For example, the potential to create hydrogeological or hydraulic barriers (e.g. via Managed Aquifer Recharge, MAR) to prevent saltwater intrusion is particularly relevant in coastal areas, where rising sea levels and groundwater withdrawal increase the risk of salinisation. Similarly, the reuse of existing subsurface spaces represents an important opportunity for sustainable resource management. Repurposing abandoned or underutilised subsurface infrastructure can reduce the need for new excavations, thereby minimising environmental impacts and associated costs, and support urban renewal (Cui et al., 2021; Qiao et al., 2024). These spaces could be adapted for various purposes, such as stormwater retention or even as protective shelters during extreme weather events. Geoenergy systems can also be strategically integrated with existing subsurface structures to create synergistic benefits and optimise resource utilisation (see e.g. Finesso & Van Ree, 2022). Incorporating these additional services into future mapping efforts would provide a more comprehensive understanding of the multifunctional potential of the subsurface in supporting climate adaptation and resilience strategies.

5.3. Usability of the maps

The discussions during the workshops (WS1 and WS2), in which authors actively participated, underscored the complexity that planners face in their daily work. The conversations frequently extended beyond subsurface issues to encompass surface-level and societal considerations related to the shaping and design of the urban physical environment. This broader perspective often included the integration of ecosystem services, highlighting the wide range of factors that must be taken into account by planners and the interconnectedness of the geophysical and biophysical environment. This emphasises that municipal planning is holistic by nature and content, meaning that thematic "single-issue problems" may not sufficiently be problematised when weighed against various planning conditions. In practice, the solution to a single problem may inadvertently create issues elsewhere—for example, constructing a hard erosion protection measure can often increase erosion rates downstream. Similarly, it may lead to the unintentional removal of options or services that could be valuable in the future, such as eliminating the potential to extract groundwater that may be needed in a drier climate. Nevertheless, authors such as Dick et al. (2017) have highlighted that urban planners are often not aware of the amount of information that is available about the subsurface, and subsurface specialists are not aware of how planners wish to use the information if they had access to it. This demonstrates, to some extent, the benefit of mapping geosystem services, as it provides a basis for a systems approach (or overarching perspective) that enables a more holistic assessment.

In line with this reasoning, the participants of WS2 generally perceived geosystem services more as a communication tool than a direct planning instrument. This aligns with international research on ecosystem services, which often highlights their conceptual rather than instrumental use (Saarikoski et al., 2018), and resonates with recent discussions on the politics of visibility in subsurface knowledge production (Craig-Thompson & Kuchler, 2025). Studies from Sweden, including Malmö, have also highlighted that it is difficult for planners to understand how ecosystem services can be operationalised in planning and decision-making (e.g. Beery et al., 2016; Schubert et al., 2018). The maps, therefore, may function less as a simple inventory and more as a decision support to articulate trade-offs among resilience options and to stage conversations about where, and under what conditions, geosystem services can be mobilised without externalising costs. The discussions during the workshop indicate that such visualisations can make alternatives tangible, help translate geoscience into formats planners already use (via the ecosystem-services frame), and provide a basis for more transparent valuation and trade-off deliberation in environmental assessment and policy. In a context where subsurface information is typically under-utilised or considered late in the planning process, maps can anchor early-stage dialogues about where geosystem services can contribute most, where synergies across hazards exist, and where supply bottlenecks or conflicts are likely to arise. In turn, this framing can better align local investments, such as synchronising shoreline protection with regional aggregate supply, coupling stormwater tunnels with material reuse strategies, or prioritising surface retrofits that simultaneously restore infiltration capacity and mitigate urban heat.

Indirect effects of geosystem services on climate resilience can be equally significant as their direct effects. Consequently, how cities plan and arrange their spaces, both above and below ground, can play a critical role. Strategic reservation of both subsurface and surface space for ecosystem and geosystem services could, ideally, enhance urban multifunctionality and foster long-term resilience. For example, recent research by Wei et al. (2024) illustrates the carbon sink potential associated with the utilisation of urban subsurface space in Chengdu, China, underscoring how subsurface planning can indirectly advance climate mitigation and adaptation objectives. Integrating such perspectives into urban planning is consistent with the multifunctional resource approach to the subsurface advocated by van Ree and van Beukering (2016), Volchko et al. (2020) and others, and further reinforces the importance of proactive subsurface strategies in the pursuit of sustainable development.

Building on this need for more integrated approaches, the operationalisation of geosystem services can be viewed as part of the broader Nature-Based Solutions (NBS) framework, offering important contributions to urban adaptation and sustainability. Increasingly, the integration of Green Infrastructure (GI) and NBS is recognised as fundamental for advancing urban resilience (Fang et al., 2023). However, in practice, the effective implementation of NBS in urban planning depends on decision-support systems that enable prioritisation of sites and solutions (e.g., Sarabi et al., 2022). Geosystem services could potentially be systematically incorporated into these frameworks, as demonstrated in Lundin Frisk et al. (2024), and add value by explicitly illustrating how decisions regarding subsurface use influence the supply of goods and services linked to broader climate resilience and sustainability objectives.

5.4. Sensitivity, validation and data gaps

The sensitivity analysis revealed that internal disagreement between the various scenarios in the developed maps was generally low to moderate, indicating that the maps are not highly sensitive to changes in assumptions regarding capacity classifications. However, it also exposed instances where certain scenarios disproportionately influenced the map outputs. This highlights the importance of transparent weighting procedures and iterative validation with end users. Without such refinements, there is a risk of overinterpreting the maps or misaligning them with local priorities.

While each map typically had one to two parameters that were the most sensitive, it is worth noting that the most sensitive parameter for both Regulation of coastal erosion and Infiltration and retention of stormwater is related to anthropogenic filling materials, underscoring its importance. A significant portion of Malmö municipality (approximately 42 %) is classified as consisting of anthropogenic filling material. These anthropogenic deposits consist of materials and landforms that have been created, reshaped, or otherwise modified by human activity. As a result, they exhibit highly heterogeneous compositions and properties that differ markedly from the geogenic materials they replace (Dijkstra et al., 2019; Taromi Sandström et al., 2024). The composition of filling materials can range from clean, well-graded crushed stone and gravel to highly variable mixtures containing construction debris, industrial by-products, or even contaminated sludge, each with distinct physical, chemical, and hydraulic characteristics (Dijkstra et al., 2019; Ljung et al., 2006; Taromi Sandström et al., 2024). Moreover, such materials are often contaminated due to historical and ongoing urban activities (e.g. Ljung et al., 2006). Despite their prevalence, the filling materials in Malmö (and in many other cities) are poorly documented in the literature and cartographic materials. In the absence of this data, in the present study, filling material was assigned a high value in relation to the service of Regulation of coastal erosion, whereas for Infiltration of stormwater, a medium value was assigned. This classification is based on the authors' estimation and is subject to considerable uncertainty and warrants further investigation. The need for greater attention to anthropogenic materials and urban soil contamination has been emphasised by previous research (Dijkstra et al., 2019; Taromi Sandström et al., 2024) and poses a significant and growing concern in urban planning worldwide.

Confidentiality concerns, unique to subsurface data, present notable challenges for geosystem service mapping, an issue less prevalent in ecosystem service mapping. The limited information available on subsurface infrastructure restricted the possibility of performing a sensitivity analysis for the maps related to subsurface space. The lack of detailed subsurface information and the lack of accessible data are problematic since, as urbanisation intensifies and surface space becomes increasingly constrained, cities are turning to the subsurface to accommodate transport systems, parking facilities, and various utility networks, including district heating, water and sewage systems, geothermal energy, and fibre-optic cables (e.g. Dick et al., 2017; Kuchler et al., 2024; Volchko et al., 2020). In response to this trend, some countries have developed underground master plans for major cities, Helsinki, Finland, being a notable example (Vähäaho, 2014). In Sweden, however, the absence of such planning frameworks, the presence of classified facilities of national or strategic interest, and the fragmented ownership and subsurface space availability pose significant challenges for municipal planning (Nordström, 2017). The lack of accessible information is partly due to the classified nature of some installations and partly due to the involvement of multiple stakeholders, which complicates efforts to obtain a comprehensive overview (Nordström, 2017). This fragmented knowledge base hinders long-term planning and the integration of subsurface considerations into climate adaptation strategies. Presently, subsurface use often follows a "first-come, first-served" principle, which further complicates coordinated development (Kuchler et al., 2024; Volchko et al., 2020).

The validation of the developed maps indicates that they are reasonably robust; however, several notable limitations were identified. Foremost is the lack of independent datasets for certain services. For example, no validation was possible for subsurface space availability due to the confidentiality of subsurface infrastructure data. This reflects a broader challenge in geosystem service mapping, data scarcity and restricted access, which constrains both accuracy and transparency. Secondly, there is the dependence on idealised geological conditions. Much of the geological information underpinning the maps is based on near-virgin conditions, which do not fully account for anthropogenic modifications. This limitation is particularly evident in the coastal erosion regulation map, where validation results diverged from expectations: areas with hard erosion measures often coincided with moderate or high potential classes. This mismatch illustrates how human interventions can obscure or alter the natural service potential, complicating validation efforts.

These findings underscore that geosystem service mapping is still in its early stages of development. To improve reliability and applicability, there is an urgent need for improved datasets and indicators, and novel datasets that focus on anthropogenic materials and human-made changes to geophysical structures and processes. In addition, future work should also explore mechanisms for data sharing and governance to overcome confidentiality barriers while safeguarding sensitive information.

5.5. Wider outlook: planning and operationalisation implications

Geosystem service potential maps could represent an emerging tool for planning, offering a visual means to illustrate the subsurface's potential contributions to urban resilience. Their role parallels that of other thematic maps used in climate adaptation, such as those addressing Urban Heat Island effects (de Groot-Reichwein et al., 2018) and urban greenery (Roest et al., 2023). These maps are particularly useful for identifying and framing problems, revealing conflicts and synergies between different services and land uses, and highlighting areas where specific services or related aspects may be at risk (Hauck et al., 2013). The perceived authority and established role of maps in planning further enhance their utility (Hauck et al., 2013). However, this perceived authority can obscure underlying uncertainties. In the context of geosystem services, geological and subsurface data often carry significant uncertainty that is not readily apparent in mapped outputs. The spatial distribution of geological formations may appear definitive, yet it typically reflects estimations that are also constrained by the resolution of the mapping scale. Even the most detailed maps generalise information beyond the accuracy of individual cells. Given the limited data and lack of precedent for such maps, concerns remain regarding their validation and accuracy. Despite these limitations, the maps hold heuristic value. They serve as educational tools that shift perceptions of the subsurface from being solely problematic to a source of potential solutions. Their visual nature facilitates discussion by making alternative planning options, or the absence of such options, more tangible.

Considering the limited body of work on geosystem services, future research should explore diverse applications and geographical contexts to better understand both benefits and barriers to implementation in planning. Operationalising geosystem services can draw on insights from the development and application of the ecosystem services concept. Given the experiences of implementing ecosystem services (Hysing, 2021; Khoshkar et al., 2020; Saarikoski et al., 2018; Sang et al., 2021), it is pertinent to reflect on the intended role of geosystem services. Like ecosystem services, the geosystem services concept has the potential to highlight society's dependence on natural systems. However, to realise their full potential, it is desirable to move beyond conceptual understanding towards instrumental application, and for ecosystem services, this has proven challenging, even in a favourable setting such as Sweden (Hysing, 2021; Sang et al., 2021).

Achieving this shift would require that the geosystem services concept is applied to address specific challenges, supported by the development of suitable tools for implementation at the local planning level, as well as thematic plans and operational documents across diverse contexts (see e.g. Khoshkar et al., 2020). Although the integration of geosystem services into planning practice remains largely a future endeavour, given the current paucity of studies, the geosystem service potential maps presented in this study represent an important foundational step. They provide a basis for incorporating geosystem services into broader planning processes, including environmental impact assessments and policy development, and open avenues for the valuation of geosystem services.

Building on these foundational steps, a key priority for future research is to systematically assess synergies and conflicts that may arise when multiple geosystem services co-occur at the same location. While this study focused on mapping individual services, recognising and evaluating these interactions are essential for integrated planning. This dimension has not yet been addressed here, reflecting the early stage of geosystem service mapping as a field. Equally important is the need to evaluate the perceived importance and value of specific geosystem services in close collaboration with municipal planners and other stakeholders. Advancing the methodology presented in this manuscript would involve incorporating such stakeholder-derived values directly into the mapping process, as exemplified in ecosystem service mapping approaches (see Andersson-Sköld et al., 2018). By embedding these perspectives, future geosystem service maps could offer even greater practical relevance by potentially enhancing decision-making and prioritisation in urban climate resilience planning.

6. Conclusion

This study presents a methodology for developing geosystem service potential maps that systematically link geophysical environments to the potential to deliver specific geosystem services. It advances the operationalisation of geosystem services by demonstrating a replicable mapping methodology and engaging end users in the evaluation of the resulting maps. Seven geosystem service potential maps were produced for Malmö municipality, each addressing geosystem services that can contribute to climate resilience: Regulation of coastal erosion, Retrieval of heat and cold from the subsurface, Infiltration and retention of stormwater, Availability of deep and shallow subsurface space, Withdrawal of groundwater, and Retrieval of construction materials. These maps were subsequently tested with municipal civil servants to assess their practical usability and to gather feedback for further refinement.

The results indicate that geosystem service potential maps, when tailored to local conditions, can serve as valuable instruments in climate resilience planning. In particular, the maps related to stormwater infiltration and retention, and subsurface temperature regulation were perceived as useful by Malmö's civil servants. However, participants also noted that the maps are better suited as communicative instruments than as direct planning tools. In this role, geosystem service potential maps act as boundary-spanning instruments, conceptual and visual instruments that facilitate dialogue across disciplinary and institutional boundaries, rather than serving as technical tools for tasks such as site selection.

Beyond the utility of the maps, these maps represent an early attempt to increase the operability of the geosystem service concept, and demonstrate its potential benefit, practical usability and its implementation challenges in a planning context. By rendering abstract geophysical processes more tangible, the maps may support planning and decision-making, and their ability to 'translate' complex geological information into formats familiar to planners, particularly by aligning with the more established ecosystem service framework, can be valuable in contexts where subsurface data is underutilised.

Despite this potential, empirical studies on the practical application of geosystem services remain limited, and few initiatives have explored the development of geosystem service indicators and maps. As such, there is a lack of guidance in the literature on how to implement geosystem services and a shortage of practical tools to support their integration into planning processes. By suggesting a list of indicators for geosystem services relevant to urban climate mitigation and proposing a replicable methodology for geosystem service potential mapping, this study contributes to the emerging discourse and provides a foundation for future research aimed at increasing the operability and retention of geosystem services in planning practices.

CRediT authorship contribution statement

Emrik Lundin-Frisk: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paula Lindgren:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Olof Taromi Sandström:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Emanuel Toft:** Writing – review & editing, Investigation. **Lorena Melgaço:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Fredrik Mossmark:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Tore Söderqvist:** Writing – review & editing, Funding acquisition. **Yevheniya Volchko:** Writing – review & editing, Funding acquisition. **Maria de Lourdes Melo Zurita:** Writing – review & editing, Funding acquisition. **Jenny Norrman:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2026.107221.

Data availability

Most of the data presented in this article is publicly available or can be provided upon request. However, some subsurface information is confidential and cannot be disclosed.Which is a bit more refined and clearer.

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