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Spatial characterization of seabed environmental conditions and geotechnical properties for the development of marine renewable energy in Sweden

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Abstract: Although knowledge of seabed properties is of high importance in selecting sites and determining technical designs and solutions for renewable energy offshore installations, it is often overlooked in marine spatial planning, owing to the absence of appropriate spatial analysis of these conditions. Identification and quantification of seabed conditions and geotechnical properties in finding safe and environmentally sustainable areas for installations of offshore renewable energy are therefore presented, using information produced in marine geological mapping. Six seabed environmental and 13 geotechnical parameters, which can be extracted from existing marine geological information and are of importance in analysing environmental conditions and planning designs are identified and presented, in addition to the suitability of various installation techniques for different areas on the Swedish seabed. Geographical information systems (GIS) are used to geospatially evaluate the different parameters in finding suitable locations and cable routes for a wave energy plant with gravity and/or suction caisson foundations. The presented categories and ranges of the environmental and geotechnical values for the various parameters have the possibility to be improved as new data are produced from future mapping. The parameters identified and presented here are valuable as they can be incorporated into multi-parameter evaluations for optimal site selection of different offshore installations.

Supplementary material: The open geological information is available at http://www.sgu.se

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Offshore renewable energy (e.g. wave and wind energy conversion) is a significant resource that has the possibility to be integrated into the Swedish energy supply (Henfridsson *et al.* 2007; Enevoldsen and Permien 2018; Nilsson *et al.* 2019). Sweden has the objective of having a 100% renewable energy supply by 2040 (Anon. 2016), where offshore renewable energy may produce up to 40 TWh a^{-1} (Swedish Energy Agency 2018). In addition to identifying areas with maximum resource potential (Strömstedt *et al.* 2017; Nilsson *et al.* 2019), identification and location of seabed conditions and areas that allow an environmentally safe and sustainable development of seabed installations and cable corridors need to be undertaken. Offshore renewable energy installations often involve arrays of devices that are either secured to the seafloor through foundations or anchors, or buried in the seabed. The power plants can occupy areas of up to a square kilometre (Ricci *et al.* 2012; Barrie and Conway 2014; Hammar *et al.* 2017; Heath *et al.* 2017; Strömstedt *et al.* 2017). The installations include cables, which are buried in or laid upon the seabed and covered, between the different devices and to the mainland. Thus, knowledge of the geological, geophysical, environmental and sediment dynamical characteristics of the seabed is critical in understanding the physical conditions in which offshore energy installations are founded, buried or anchored (Goff *et al.* 2004; Thompson and Beasley 2012; Barrie and Conway 2014; Heath *et al.* 2017; Guinan *et al.* 2020). However, little work has been done so far to investigate and map the geological, geophysical and environmental properties, and their occurrences, which have to be known when selecting sites, planning and designing for offshore renewable energy, such as wave and wind energy conversion installations, in Swedish seawaters.

The marine geology plays a major role in controlling the distinct material that gives the geotechnical engineering properties of the sediments and substrate for biota as well as indications of sediment dynamics and bottom currents for different areas (Thompson and Beasley 2012; Zajac *et al.* 2013; Barrie and Conway 2014; Heath *et al.* 2017; Kaskela *et al.* 2017; Guinan *et al.* 2020). Because certain types of foundations and anchors perform better in some sediments or rock types than others (Thompson and Beasley 2012), certain biota prefer some substrates to others (Zajac *et al.* 2013; Kaskela *et al.* 2017) and certain sediments and sediment dynamic environments may contain pollutants or be at risk of landslides, knowledge of the marine geological environment and sediment distribution is crucial. Here, we therefore present such an identification, categorization, quantification and mapping of the geological, geotechnical and environmental variables that are appropriate to use in finding and planning areas for offshore renewable energy. The data are originally based on hydroacoustic raw data and data from samples and seabed observations, which are used in producing marine geological maps. Existing as well as new information derived from geological mapping can be translated in the proposed way and be used for offshore engineering and environmental analysis, in both overview planning and detailed site mapping. The terminology used for the marine geology classification is also adapted into the international data transfer standard of digital geoscientific information, making it useful worldwide.

Material and methods

Geospatial multi-parameter evaluation method

Here we employ geographical information systems (GIS) for the geospatial multi-parameter evaluation. Using GIS allows us to use

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the variety of environmental and geotechnical attributes derived from spatial information that different areas possess and to consider resources as well as all other uses and interests (Carver 1991). Advantages in using this approach are its applicability by immediately generating visual information on geographical maps for stakeholder engagement, as well as to communicate alternative scenarios and the assessment of trade-offs (Flocard *et al.* 2016). It has also earlier been used in, for example, site selection for wind farms, wave energy projects and aquaculture (Azzellino *et al.* 2013; Davies *et al.* 2014; Gimpel *et al.* 2015; Cavazzi and Dutton 2016; Flocard *et al.* 2016).

Assigned numerical values for defined classes in the considered parameters are multiplied by a given criterion weight of relative importance for each of the parameters. The sum of the products derived from these factors gives a common Suitability Index (SI) for different areas (Eastman 1999):

$$\mathrm{SI} = \sum_{i=1}^{n} wiXi. \tag{1}$$

where wi is a numerical value assigned for a class in parameter i, and Xi is a criterion weight for parameter i. Because the parameters are measured in different units and could be given a negative factor, there is a need to transform the products to a normalized scale, normally ranging from zero to unity, where $\mathrm{SI} = \sum_{i=1}^{n} wiXi$zero is considered the least suitable and unity is the best possible value (Carver 1991):

$$\mathrm{SI}_{\mathrm{normalized}} = \frac{\mathrm{SI} - \mathrm{SI}_{\mathrm{min}}}{\mathrm{SI}_{\mathrm{max}} - \mathrm{SI}_{\mathrm{min}}}. \tag{2}$$

The normalizing is performed as above by first shifting the values such that the most negative become zero.

Choice and criterion weighting of parameters

The main objective of this study is to identify the safest and most sustainable sites, in terms of both physical installations and benthic habitats, for renewable power plants using information on the seabed's geotechnical properties and environmental conditions. A multi-parameter evaluation following the process of Nobre *et al.* (2009) and Şan *et al.* (2021) has been carried out. The parameters and their internal classes and assigned weightings used and considered for site, area and foundation evaluations are based on conclusions from experts with geological, geotechnical and environmental background and experience. Some of the parameters are also usually analysed in environmental impact assessments for marine installations. Six environmental and 13 geotechnical parameters derived from the geological information are classified and weighted within each parameter so that they can be applied in summarizing a score such that the higher the score the better a site or an area is for a marine installation or type of foundation. Because low weighting values for some parameters (e.g. sediment dynamics and heterogeneity of the seabed) are considered as better, these weightings are given negative values (i.e. multiplied by −1). The importance of each parameter is then evaluated and given a score (i.e. a multiplication factor) yielding a total weighting factor for the parameter for different sites, areas and foundation types. The suitability index is calculated and normalized to a scale ranging from zero to unity.

An example is presented in this paper where six environmental and four geotechnical parameters are combined and calculated to obtain an $\mathrm{SI}_{\mathrm{normalized}}$, as in equations (1) and (2), for different areas using the functions weighting sum and map algebra in ArcGIS 10.5.1 (ESRI, ArcGIS Platform). This is done to identify potential good sites and areas for installation of renewable energy plants within the Swedish Exclusive Economic Zone (EEZ).

The SI derived from each parameter and major criterion was normalized to a common scale of zero to unity, where unity is considered the best possible value and zero the least suitable, to provide the basis for using other types of parameters in future final site ranking calculations (SI). The other parameters used to reach such a final SI can, for example, include the following:

- assessment of the resource (i.e. wave energy), as it is a clear indicator of the energy resource available and the economic potential (see, e.g. Nilsson *et al.* 2019);
- bathymetry, which excludes areas that are too shallow or too deep, or have a slope that is too high (i.e. >10°) for gravity foundations or would be susceptible to landslides, as well as parameters derived from bathymetric information, such as rugosity, which can be a measure of an areas' bathymetric heterogeneity, as well as Bathymetric Position Index (BPI), which effectively highlights positive and negative features of the terrain;
- distance to land and infrastructure;
- ice occurrence;
- pre-existing restrictions related to the protection and maintenance of biodiversity;
- shipping and fishing density;
- military interests;
- other users and stakeholders as a measure of detection of potential conflict of use with other socio-economic users of the marine space.

The geological data

Terminology and information

The available marine geological information within the Swedish territorial sea and EEZ has a terminology in which the sediments are categorized into 14 classes according to their depositional environment, grain size distribution and content of organic matter (Fig. 1 and Tables 1–3). The depositional environment is categorized as glacial, when the sediments are old and deposited in a glacial-related environment, or postglacial, when the sediments are younger, or were formed and deposited in a non-glacial environment. The classification of grain size distribution is based on a modified version of the Atterberg grade scale (Hansbo *et al.* 1984; Svenska Geotekniska Föreningen 2016). The sediment types are mainly classified according to the dominant grain size but also according to the clay content, expressed as percentage of weight of all particles smaller than 20 mm. The content of organic matter is expressed as per cent dry matter in the sediment (see, e.g. Nyberg 2016*b*).

This geological terminology thus provides information on, for example, age, event, environmental and process settings for different sediments, which give indications on seabed environment, physical and geotechnical properties, and probable sediment stratigraphy for different areas. In addition, chemical analyses on younger sediments give information on the distribution of pollutants.

For example, if till is found on the seabed without another type of overlying sediment and without finer fractions in the upper part of the deposit, it is indicative of an exposed and/or a non-accumulating environment. Till is a sediment that is glacial-related through being mechanically deposited in a subglacial setting. It consists of grains of all sizes and has a minor organic content. Therefore, till on the seabed indicates a low sediment dynamic seabed through the presence of coarse immobile particles and a seabed that has minor or no accumulation of fine particles, organic material and pollutants. Furthermore, the seabed is heterogeneous, contains boulders, is hard and has a high vertical bearing capacity. If postglacial clay,

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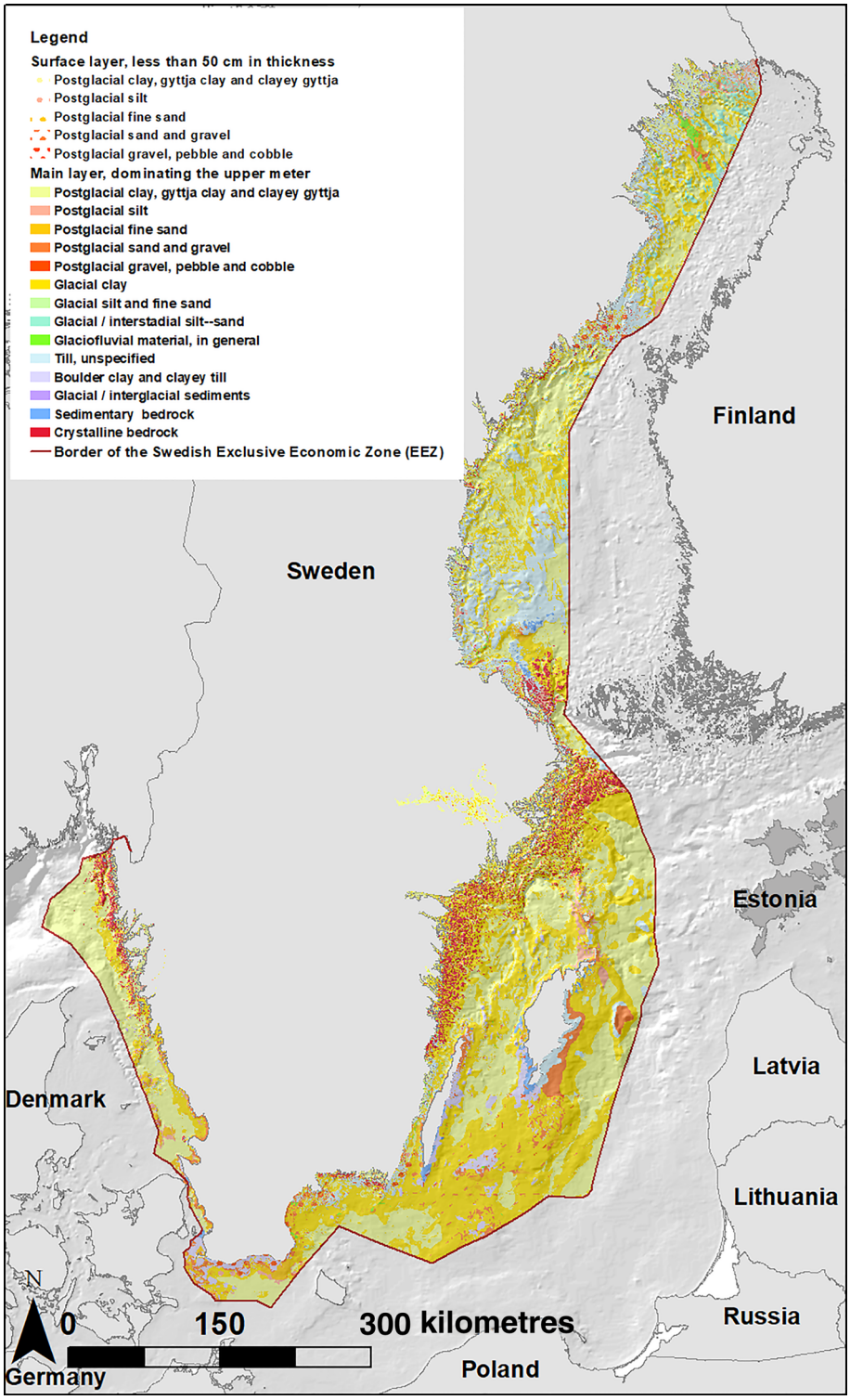

Fig. 1. Existing marine geological information for the Swedish seabed presented in 14 different classifications in geological terminology. The information is also divided into two data layers: the main layer (the sediment or bedrock that dominates the upper 1 m of the seabed), and the thin surface layer (the sediment found in the surface with a thickness less than 50 cm). The same classifications and terminology are used both for the thin surface layer and the dominating layer. The shaded relief is taken from Seifert *et al.* (2001).

gyttja clay or clayey gyttja is found on the seabed, it is indicative of a low-exposed environment with low sediment dynamics. Postglacial clay, gyttja clay or clayey gyttja is formed and deposited in a non-glacial environment, as an outwash or reworked from the original glacial deposit. The presence of these sediments therefore also indicates a seabed with moderate to high accumulation of fine particles and organic matter as well as possible pollutants. The seabed is homogeneous, contains no boulders and has a low bearing capacity.

The terminology used for the marine geology classification is also incorporated into the XML-based data transfer standard for the exchange of digital geoscientific information, GeoSciML (http://www.geosciml.org/; Sen and Duffy 2005). GeoSciML is an International Organization for Standardization (ISO) General Feature Model (ISO19101 (2014), ISO19109 (2015)) implementation of portions of the North American Data Model (USGS, https://ngmdb.usgs.gov/www-nadm/; Anon. 2004) and the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) XMML model. GeoSciML also provides models for concepts at the immediate periphery of geological mapping, such as boreholes, geological specimens and laboratory analysis. The GeoSciML data standard is underpinned by several established Open Geospatial Consortium (OGC) and ISO standards and is used as the geoscientific data transfer standard for exchange of geological

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Table 1. *The 14 classifications in geological terminology and their translated classes and assigned weighting values for six environmental parameters*

Marine geological class	Environmental parameter											
	Sediment dynamics, extent of sediment transport and size of sediment particles that are transported (3 classes: low, moderate, high)	Sediment dynamics, extent of sediment transport and size of sediment particles transported (3 weighting values: 1, 2, 3)	Heterogeneity of the seabed material (3 classes: low, moderate, high)	Heterogeneity of the seabed material (3 weighting values: 1, 2, 3)	Exposure to bottom currents (3 classes: low, moderate, high)	Exposure to bottom currents (3 weighting values: 1, 2, 3)	Presence of boulders according to SGF 2016 (4 classes: none, slight, moderate, high)	Presence of boulders according to SGF 2016 (4 weighting values: 1, 2, 3, 4)	Rate of accumulation of fine particles and organic material (3 classes: low, moderate, high)	Rate of accumulation of fine particles and organic material (3 weighting values: 1, 2, 3)	Risk of dispersion of contaminants buried in sediments (3 classes: low, moderate, high)	Risk of dispersion of contaminants buried in sediments (3 weighting values: 1, 2, 3)
Crystalline bedrock	Predominantly a low-dynamic seabed where temporal and local mobilization, transport and deposition of Very Coarse–Coarse–Fine particles occur	1	Low–moderate	2	Moderate–high	3	None (0%)–slight (<5%)–moderate (5–20%)–high (>20%)	2	Low	1	Low	1
Sedimentary bedrock	Predominantly a low-dynamic seabed where temporal and local mobilization, transport and deposition of Very Coarse–Coarse–Fine particles occur	1	Low–moderate	2	Moderate–high	3	None (0%)–slight (<5%)–moderate (5–20%)–high (>20%)	2	Low	1	Low	1
Till, unspecified	Predominantly a low-dynamic seabed where temporal and local mobilization, transport and deposition of Very Coarse–Coarse–Fine particles occur	1	Moderate–high	3	Moderate–high	3	None (0%)–slight (<5%)–moderate (5–20%)–high (>20%)	4	Low	1	Low	1
Boulder Clay and clayey Till	Predominantly a low-dynamic seabed where temporal and local mobilization, transport and deposition of Very Coarse–Coarse–Fine particles occur	1	Moderate–high	3	Moderate–high	3	None (0%)–slight (<5%)–moderate (5–20%)–high (>20%)	3	Low	1	Low	1
Glaciofluvial material, in general	Predominantly a low- to moderate-dynamic seabed where temporal and	2	Low–moderate–high	3	Moderate–high	3	None (0%)–slight (<5%)–moderate	3	Low	1	Low	1

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	local mobilization, transport and deposition of Very Coarse–Coarse–Fine particles occur						(5–20%)–high (>20%)						
Glacial Silt and fine Sand	Predominantly a low-dynamic seabed where temporal and local mobilization, transport and deposition of Fine particles occur	1	Low–moderate	1	Moderate–high	2	None (0%)–slight (<5%)	1	Low	1	Low	1	
Glacial Clay	Predominantly a low-dynamic seabed where temporal and local erosion, transport and accumulation of Coarse and Fine particles occur	1	Moderate–high	2	Moderate–high	2	None (0%)–slight (<5%)–moderate (5–20%)	2	Low	1	Low	1	
Glacial/interstadial Silt–Sand	Predominantly a low-dynamic seabed where temporal and local mobilization, transport and deposition of Coarse and Fine particles occur	1	Low–moderate	1	Moderate–high	2	None (0%)–slight (<5%)	1	Low	1	Low	1	
Glacial/interglacial sediments	Predominantly a low-dynamic seabed where temporal and local mobilization, transport and deposition of Coarse and Fine particles occur	1	Moderate–high	2	Moderate–high	2	None (0%)–slight (<5%)	1	Low	1	Low	1	
Postglacial Gravel, Pebble and Cobble	Predominantly a low- to moderate-dynamic seabed where temporal and local mobilization, transport and deposition of Very Coarse–Coarse–Fine particles occur	2	Moderate–high	3	Moderate–high	3	None (0%)–slight (<5%)–moderate (5–20%)	2	Low	1	Low–moderate, may occur in depressions and excavations	2	
Postglacial Sand and Gravel	Predominantly a moderate- to high-dynamic seabed where erosion and transport of mainly	2	Low–moderate	2	Moderate–high	3	None (0%)–slight (<5%)	1	Low–moderate, may occur in depressions	2	Low–moderate, may occur in depressions and excavations	2	

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Table 1. *(Continued)*

Marine geological class	Environmental parameter											
	Sediment dynamics, extent of sediment transport and size of sediment particles that are transported (3 classes: low, moderate, high)	Sediment dynamics, extent of sediment transport and size of sediment particles transported (3 weighting values: 1, 2, 3)	Heterogeneity of the seabed material (3 classes: low, moderate, high)	Heterogeneity of the seabed material (3 weighting values: 1, 2, 3)	Exposure to bottom currents (3 classes: low, moderate, high)	Exposure to bottom currents (3 weighting values: 1, 2, 3)	Presence of boulders according to SGF 2016 (4 classes: none, slight, moderate, high)	Presence of boulders according to SGF 2016 (4 weighting values: 1, 2, 3, 4)	Rate of accumulation of fine particles and organic material (3 classes: low, moderate, high)	Rate of accumulation of fine particles and organic material (3 weighting values: 1, 2, 3)	Risk of dispersion of contaminants buried in sediments (3 classes: low, moderate, high)	Risk of dispersion of contaminants buried in sediments (3 weighting values: 1, 2, 3)
	coarse particles occur. Accumulation occurs in depressions or obstructions											
Postglacial fine Sand	Predominantly a high-dynamic seabed where mobilization and transport of mainly fine- and medium-grained sand particles occur. Deposition occurs in depressions or obstructions	3	Low	1	Moderate–high	3	None (0%)–slight (<5%)	1	Low–moderate, may occur in depressions	2	Low–moderate, may occur in depressions and excavations	2
Postglacial Silt	Predominantly a low-dynamic seabed where temporal and local mobilization, transport and deposition of mainly silt, but also clay and fine sand particles as well as organic material occur	1	Low	1	Low–moderate	1	None (0%)–slight (<5%)	1	Moderate–high	2	Moderate–high	2
Postglacial Clay, gyttja Clay and clayey Gyttja	Predominantly a low-dynamic seabed where deposition of mainly clay particles and organic material occurs. Temporal and local transport may occur	1	Low	1	Low	1	None (0%)–slight (<5%)	1	Moderate–high	3	Moderate–high	3

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Table 2. *The 14 classifications in geological terminology and their translated classes, assigned weighting values for eight relevant parameters, and, where applicable, intervals for technical units*

Marine geological class	Geotechnical parameter										
	Particle size, according to SS-EN ISO 14668 (3 classes: Fine, Coarse, Very Coarse)	Particle sorting and grading according to SS-EN ISO 14668 (3 classes: poorly, moderately, well)	Content of organic material (4 classes: none or very low, low, moderate, high)	Content of organic material (4 weighting values: 1, 2, 3, 4)	Bulk density (tonnes m^{-3}) water saturated (ρm)	Bulk density (tonnes m^{-3}) below water (ρ')	Bulk density (tonnes m^{-3}) above water (ρ)	Cohesion (4 classes: none, low, moderate, high)	Cohesion (4 weighting values: 1, 2, 3, 4)	Shear strength (5 classes: very low, low, moderate, high, very high)	Shear strength (5 weighting values: 1, 2, 3, 4, 5)
Crystalline bedrock	n.a.	n.a.	n.a.	n.a.	2.5–2.8	2.5–2.8	2.5–2.8	High (200–400 kPa)	4	Very high (>10 GPa)	5
Sedimentary bedrock	n.a.	n.a.	n.a.	n.a.	2.4–2.6	2.4–2.6	2.4–2.6	High (100–400 kPa)	4	High (>3 GPa)	4
Till, unspecified	Fine–Coarse–Very Coarse	Poorly	None or very low (0–2%)	1	2.1–2.4	1.1–1.4	1.8–2.3	None (0 kPa)	1	Low (<50 kPa)–moderate (50–100 kPa)	3
Boulder Clay and clayey Till	Fine–Coarse–Very Coarse	Poorly	None or very low (0–2%)	1	2.0–2.2	1.0–1.2	2.0–2.2	Boulder Clay, low (5 kPa), moderate (<50 kPa); clayey Till, high (200–600 kPa)	2, 3 or 4	Low (<50 kPa)–moderate (50–100 kPa)–high (>100 kPa)	3
Glaciofluvial material, in general	Coarse–Very Coarse	Moderately–well	None or very low (0–2%)	1	1.8–1.9	0.8–0.9	1.6–1.8	None (0 kPa)	1	Moderate (50 kPa)–high (>100 kPa)	4
Glacial Silt and fine Sand	Fine–Coarse–Very Coarse	Moderately–well	None or very low (0–2%)	1	1.7–1.8	0.7–0.8	1.7–1.8	None (0 kPa)	1	Low (<50 kPa)–moderate (50–100 kPa)	2
Glacial Clay	Fine–Coarse	Moderately–well	None or very low (0–2%)	1	1.6–1.7	0.7–1.1	1.6–1.7	Low (5 kPa) to high (>50 kPa) (overconsolidated)	2	Very low (<20 kPa)–low (<50 kPa)	2
Glacial/interstadial Silt–Sand	Fine–Coarse	Moderately–well	None or very low (0–2%)	1	1.7–2.0	0.7–1.0	1.6–2.0	None (0 kPa)	1	Low (<50 kPa)–moderate (50–100 kPa)	3
Glacial/interglacial sediments	Fine–Coarse	Well (within each layer)	None or very low (0–2%)	1	1.7–2.0	0.7–1.0	1.6–1.7	None (0 kPa)–moderate (<50 kPa)	1	Low (<50 kPa)–moderate (50–100 kPa)	3

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Table 2. *(Continued)*

Marine geological class	Geotechnical parameter										
	Particle size, according to SS-EN ISO 14668 (3 classes: Fine, Coarse, Very Coarse)	Particle sorting and grading according to SS-EN ISO 14668 (3 classes: poorly, moderately, well)	Content of organic material (4 classes: none or very low, low, moderate, high)	Content of organic material (4 weighting values: 1, 2, 3, 4)	Bulk density (tonnes m^{-3}) water saturated (ρm)	Bulk density (tonnes m^{-3}) below water (ρ')	Bulk density (tonnes m^{-3}) above water (ρ)	Cohesion (4 classes: none, low, moderate, high)	Cohesion (4 weighting values: 1, 2, 3, 4)	Shear strength (5 classes: very low, low, moderate, high, very high)	Shear strength (5 weighting values: 1, 2, 3, 4, 5)
Postglacial Gravel, Pebble and Cobble	Coarse–Very Coarse	Moderately–well	None or very low (0–2%)–low (2–6%)	1–2	1.8–2.0	0.8–1.0	1.4–1.9	None (0 kPa)	1	Moderate (50–100 kPa)	3
Postglacial Sand and Gravel	Coarse	Moderately–well	None or very low (0–2%)–low (2–6%)	1–2	2.0–2.2	1.0–1.2	1.8–1.9	None (0 kPa)	1	Moderate (50–100 kPa)	3
Postglacial fine Sand	Fine–Coarse	Well	None or very low (0–2%)–low (2–6%)	1–2	1.8–2.0	0.8–1.0	1.6–1.8	None (0 kPa)	1	Low (<50 kPa)–moderate (50–100 kPa)	2
Postglacial Silt	Fine	Well	None or very low (0–2%)–low (2–6%)–moderate (6–20%)	1–3	1.4–1.7	0.4–0.7	1.4–1.7	None (0 kPa)–moderate (<50 kPa)	1, 2 or 3	Very low (<20 kPa)–low (<50 kPa)	1
Postglacial Clay, gyttja Clay and clayey Gyttja	Fine	Well	Low (2–6%)–moderate (6–20%)–high (>20%)	2–4	1.4–2.0	0.4–1.0	1.4–2.0	Low (5 kPa) to high (>50 kPa) (overconsolidated)	2, 3 or 4	Very low (<20 kPa)–low (<50 kPa)	1

Marine geological class	Geotechnical parameter									
	Permeability (3 classes: low, moderate, high)	Permeability (3 weighting values: 1, 2, 3)	Friction angle (4 classes: none, low, moderate, high)	Friction angle (4 weighting values: 1, 2, 3, 4)	Elasticity (stiffness) (Young's modulus) (4 classes: none, low, moderate, high)	Elasticity (stiffness) (Young's modulus) (4 weighting values: 1, 2, 3, 4)	Vertical bearing capacity (5 classes: very low; low, moderate, high, very high)	Vertical bearing capacity (5 weighting values: 1, 2, 3, 4, 5)	Excavation capacity (5 classes: very high, high, moderate, low, very low)	Excavation capacity (5 weighting values: 1, 2, 3, 4, 5)
Crystalline bedrock	Low (10^{-11}–10^{-7} m s^{-1})	1	Moderate (20–30°)–high (>30°). Depends on rock quality	3 or 4	High (>20 GPa)	4	Very high (≫300 kN m^{-2})	5	Very low (5)	5
Sedimentary bedrock	Low (10^{-11}–10^{-7} m s^{-1})	1	Moderate (20–30°)–high (>30°). Depends on rock quality	3 or 4	High (>9 GPa)	4	High–very high (≫300 kN m^{-2})	5	Low–very low (4–5)	4
Till, unspecified	Low (10^{-10}–10^{-7} m s^{-1})	1	Moderate (20–30°)–high (>30°)	3	Moderate (<30 MPa)–high (<90 MPa)	3–4	Moderate–high (100–200 kN m^{-2})	4	Moderate–very low (3–5)	4

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Boulder Clay and clayey Till	Low (10^{-11}–10^{-7} m s^{-1})	1	None (cohesion)–moderate (20–30°)–high (>30 °)	1 or 3–4	Low (<10 MPa)–moderate (<30 MPa)–high (<90 MPa)	2–4	Moderate–high (100–200 kN m^{-2})	4	Moderate–very low (3–5)	4
Glaciofluvial material, in general	Moderate (10^{-7}–10^{-3} m s^{-1})–high (10^{-3}–1 m s^{-1})	2–3	Moderate (20–30°)–high (>30°)	3	Moderate (<30 MPa)–high (<70 MPa)	3–4	Moderate–high (100–150 kN m^{-2})	4	Very high–low (1–4)	3
Glacial Silt and fine Sand	Moderate (10^{-7}–10^{-3} m s^{-1})	2	None–low (<20°)–moderate (20–30°)	1–2	Low (<10 MPa) (silty)–moderate (<30 MPa) (loose)	2–3	Low–moderate–high (25–100 kN m^{-2})	3	Very high–moderate (1–3)	2
Glacial Clay	Low (10^{-11}–10^{-7} m s^{-1})	1	None–low (<20°)	1–2	None	1	Low–moderate–high (25–100 kN m^{-2})	3	Very high–moderate (1–3)	2
Glacial/interstadial Silt–Sand	Low (10^{-11}–10^{-7} m s^{-1})–moderate (10^{-7}–10^{-3} m s^{-1})	1–2	Low (<20°)–moderate (20–30°)	2–3	Low (<10 MPa) (silty)–moderate (<30 MPa) (loose)	2–3	Low–moderate–high (25–75 kN m^{-2})	3	Very high–moderate (1–3)	2
Glacial/interglacial sediments	Low (10^{-11}–10^{-7} m s^{-1})–moderate (10^{-7}–10^{-3} m s^{-1})	1–2	Low (<20°)–moderate (20–30°)–high (<30°)	2–4	Low (<10 MPa)–moderate (<30 MPa)–high (<50 MPa)	2–4	Low–moderate–high (25–>100 kN m^{-2})	3	High–moderate–low (2–4)	3
Postglacial Gravel, Pebble and Cobble	Moderate (10^{-7}–10^{-3} m s^{-1})–high (10^{-3}–1 m s^{-1})	2–3	Moderate (20–30°)–high (>30°)	3–4	Moderate (<30 MPa)–high (<70 MPa)	3–4	Moderate–high (100–150 kN m^{-2})	4	Very high–moderate (1–3)	2
Postglacial Sand and Gravel	Moderate (10^{-7}–10^{-3} m s^{-1})–high (10^{-3}–1 m s^{-1})	2–3	Moderate (20–30°)–high (>30°)	3–4	Low (<10 MPa)–moderate (<30 MPa)	2–3	Moderate–high (>100 kN m^{-2})	4	Very high–moderate (1–3)	2
Postglacial fine Sand	Moderate (10^{-7}–10^{-3} m s^{-1})	2	Low (<20°)–moderate (20–30°)	2–3	Low (<10 MPa)–moderate (<30 MPa)	2–3	Low–moderate–high (50–75 kN m^{-2})	3	Very high–moderate (1–3)	2
Postglacial Silt	Low (10^{-11}–10^{-7} m s^{-1})–moderate (10^{-7}–10^{-3} m s^{-1})	1–2	None–low (<20°)	1–2	Low (<10 MPa)–moderate (<30 MPa)	2–3	Very low–low (<50 kN m^{-2})	2	Very high–moderate (1–3)	2
Postglacial Clay, gyttja Clay and clayey Gyttja	Low (10^{-11}–10^{-7} m s^{-1})	1	None	1	None	1	Very low–low (<50 kN m^{-2})	2	Very high–high (1–2)	1

n.a., not applicable.

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Table 3. *The suitability and performance for securing constructions with eight installation techniques (i.e. type of foundation and anchor) for different sediments or bedrock*

Marine geological class	Installation technique							
	Performance for pile (drilled + grout anchor) type of foundations (3 classes: not well, moderate, well)	Performance for pile (driven) type of foundations (3 classes: not well, moderate, well)	Performance for gravity-based (seabed slope <10°) type of foundations (2 classes: moderate, well)	Performance for pile (drilled) type of anchors (3 classes: not well, moderate, well)	Performance for gravity-based type of anchors (3 classes: not well, moderate, well)	Performance for direct embedment (no vertical download) type of anchors (3 classes: not well, moderate, well)	Performance for drag embedment (no vertical up and download) type of anchors (3 classes: not well, moderate, well)	Performance for suction caisson type of foundations (4 classes: not well, not well to moderate, moderate to well, well)
Crystalline bedrock	Well	Not well–moderate	Well	Moderate–well	Moderate	Not well (difficult to install)	Not well	Not well
Sedimentary bedrock	Not well–moderate–well. Depends on type of bedrock quality. Works in general for rock type 1–2	Not well–moderate–well	Well	Not well–moderate–well. Depends on type of bedrock quality. Works in general for rock type 1–2	Moderate	Not well (difficult to install)	Not well	Not well
Till, unspecified	Well. Consider alkaline derusting and corrosive sediments	Well if no boulders	Well	Well if no boulders	Well	Well if no boulders	Not well–moderate (no boulders)	Not well
Boulder Clay and clayey Till	Moderate–well. Consider alkaline derusting and corrosive sediments	Well if no boulders	Well	Well if no boulders	Well	Moderate–well (difficult to install if boulders)	Not well–moderate (no boulders)	Not well
Glaciofluvial material, in general	Moderate–well. Consider alkaline derusting	Well if no boulders	Well	Well if no boulders	Well	Moderate–well (difficult to install if boulders)	Not well–moderate (no boulders)	Not well–moderate
Glacial Silt and fine Sand	Moderate. Consider alkaline derusting and corrosive sediments	Well	Well	Moderate–well	Well	Well	Well	Not well–moderate
Glacial Clay	Moderate. Consider alkaline derusting and corrosive sediments	Well if no boulders	Well	Moderate–well if no boulders	Well	Well if no boulders	Moderate–well (no boulders)	Not well–moderate
Glacial/ interstadial Silt–Sand	Moderate. Consider alkaline derusting and corrosive sediments	Well	Well	Moderate–well	Well	Well	Well	Not well–moderate
Glacial/ interglacial sediments	Not well–moderate. Consider alkaline derusting and corrosive sediments	Well	Well	Moderate–well	Well	Well	Well	Not well–moderate
Postglacial Gravel, Pebble and Cobble	Moderate–well. Consider alkaline derusting and corrosive sediments	Well	Well	Well	Well	Moderate–well (difficult to install if boulders)	Not well–moderate (no boulders)	Not well–moderate
Postglacial Sand and Gravel	Moderate–well. Consider alkaline derusting and corrosive sediments.	Well	Well	Well	Well	Well	Well	Moderate–well

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Postglacial fine Sand	Moderate–well. Consider alkaline derusting and corrosive sediments	Moderate–well	Moderate – Well	Well	Well	Well	Moderate–well
Postglacial Silt	Moderate. Consider alkaline derusting and corrosive sediments	Moderate–well	Moderate–well	Moderate–well	Well	Well	Moderate–well
Postglacial Clay, gyttja Clay and clayey Gyttja	Moderate. Consider alkaline derusting and corrosive sediments	Moderate	Moderate–well	Not well–moderate	Well	Well	Well

Modified after Thompson and Beasley (2012), Heath *et al.* (2017) and Tyréns (pers. comm. 2018).

information between countries on both the global level (e.g. OneGeology, http://www.onegeology.org/home.html), and the European level (e.g. the Inspire Directive; Anon. 2007).

For these reasons, there are possibilities to translate and retrieve, from the 14 classes of geological terminology used by the Geological Survey of Sweden, approximate information on the seabed's environmental conditions and geotechnical properties as well as for exchange on an international level. We have identified six seabed environmental and 13 geotechnical parameters, which can be extracted from the marine geological information and are of importance in analysing environmental conditions and planning designs for secure and sustainable offshore renewable energy installations.

The data

The data and terminology used here are from the Geological Survey of Sweden's (SGU) project-financed regular mapping during 1977–2016 (Figs 1–3). The data acquired to produce the marine geological maps come, depending on area and year, from the following sources: (1) side-scan sonar and multibeam echo sounder, which give information on the horizontal distribution of seabed sediments, morphology and water depths; (2) sediment profiler, which gives high-resolution information on stratigraphy for the upper parts of the seabed; (3) shallow seismic surveys, which give low-resolution information on the stratigraphy down to the bedrock surface (Axberg *et al.* 1986; Elhammer *et al.* 1986; Kjellin *et al.* 1986; Berg *et al.* 2005; Cato and Persson 2012, 2013; Nordgren 2012; Nyberg and Bergman 2012; Nyberg and Thelander 2012; Slagbrand and Lundqvist 2012; Lind and Bergman 2013*a*, *b*; Malmberg-Persson *et al.* 2014, 2016; Slagbrand and Klingberg 2015; Cato *et al.* 2016; Lind 2016; Nyberg 2016*a*, *b*, *c*). In addition to these hydroacoustic datasets, ground-truthing in the form of seabed sampling and visual observations of the seabed is carried out, as well as chemical analyses on younger sediments.

The regular mapping has been carried out with the purpose of reporting the nature of the seabed at scales of 1:25 000 (Malmberg-Persson *et al.* 2014, 2016), 1:100 000 (Axberg *et al.* 1986; Elhammer *et al.* 1986; Berg *et al.* 2005; Cato and Persson 2012, 2013; Nordgren 2012; Nyberg and Bergman 2012; Nyberg and Thelander 2012; Slagbrand and Lundqvist 2012; Lind and Bergman 2013*a*, *b*; Klingberg 2015*a*, *b*; Slagbrand and Klingberg 2015) and 1:500 000 (Cato *et al.* 2016; Lind 2016; Nyberg 2016*a*, *b*, *c*). At 1:25 000 and 1:100 000 scale, the survey lines have been separated by about 50–1000 m to obtain full coverage of the seabed surface by multibeam echo sounder and/or side-scan sonar (see Fig. 2). At 1:100 000 scale, no areas less than 3000 m^2, *c.* 50 × 60 m, are shown. At 1:500 000 scale, the survey lines have been separated by 13 km, to obtain a cost-effective survey of the Swedish seabed (see Fig. 2). In the areas between the survey lines, the geological nature of the seabed at 1:500 000 scale is reported from existing sea chart information and, where they occur, SGU, other agency, consultants and university investigations (see Cato *et al.* 2016; Lind 2016; Nyberg 2016*a*, *b*, *c*).

Because the sediments that dominate the upper 1 m of the seabed often are covered by a thin layer of another sediment with a thickness of less than 50 cm, the marine geology of the seabed surface, at scales of 1:25 000 and 1:100 000, is presented, where this is found, in two data layers (see Fig. 1): the main layer, which shows the type of sediment or bedrock that dominates the upper 1 m of the seabed, and a thin surface layer, which shows the sediment found at the surface with a thickness less than 50 cm. The sediment that dominates the upper 1 m forms the morphology and main property of the seabed whereas the thin surface layers could consist of, for example, mobile layers of sand and silt, coarser-grained residual material that overlies clay or till, and finer-grained non-mobile accumulated sediments.

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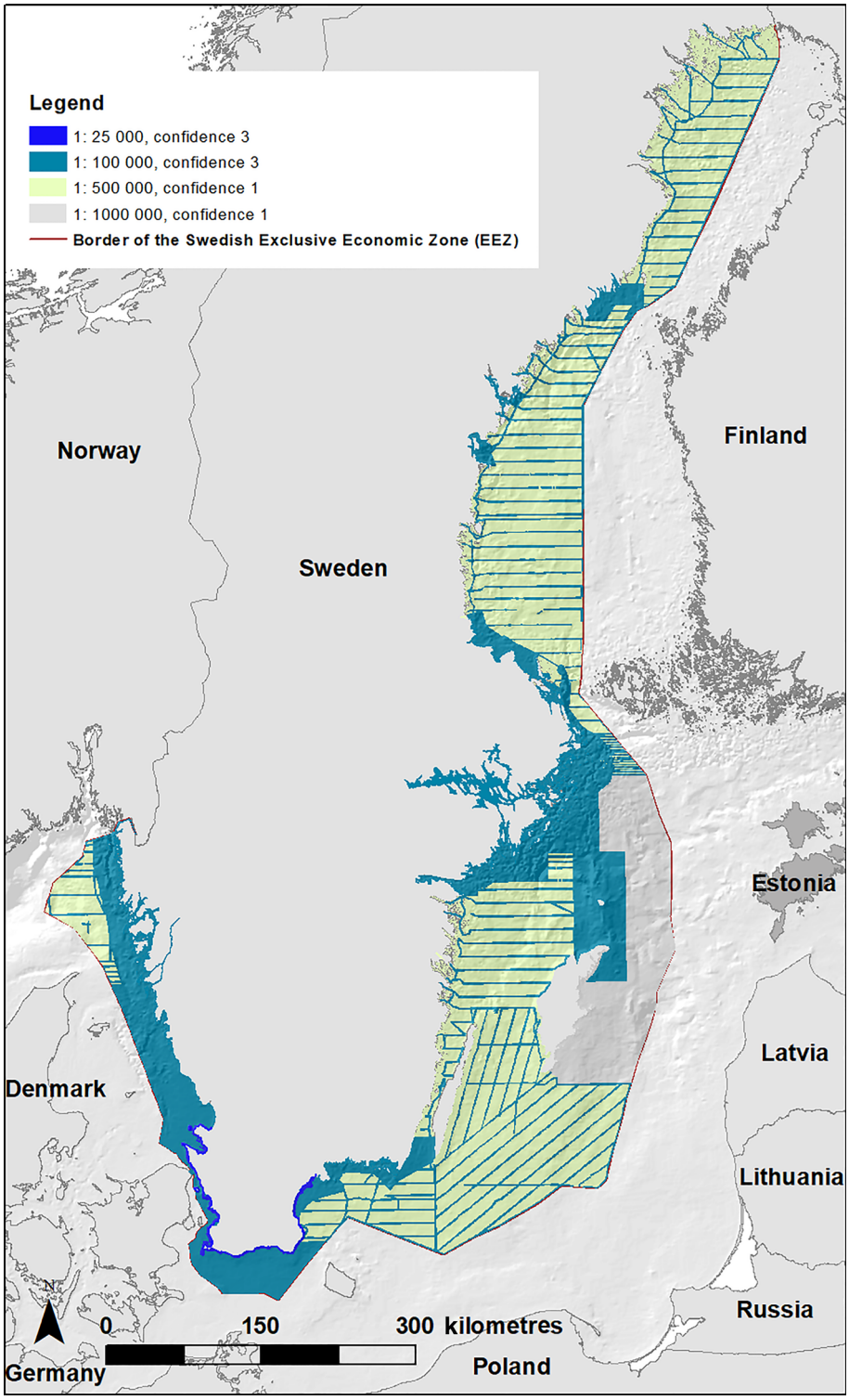

Fig. 2. The presentation scales of marine geological maps produced for different areas and associated confidence scores. The highest score representing the 'best' map according to the method of assessing accuracy, and uncertainty is four (Lillis 2016).

The stratigraphy retrieved from interpreting the hydroacoustic datasets verified by ground-truthing is presented using the same terminology as in the spatial marine geological maps. This means that vertical geotechnical information on the seabed also can be retrieved and presented from the marine geological survey data information (see Fig. 3), resulting in high-resolution 3D models showing the properties of the seabed below the seabed surface.

Confidence of the data

The confidence, which is an assessment of the accuracy and uncertainty of the resulting maps, based on remote sensing coverage, distinctness of class boundaries and amount of sampling for external validation, has been evaluated according to Lillis (2016) (see Fig. 2). In general, the method is a simple three-step decision tree, and the final score is the sum of the points awarded for each criterion and ranges between zero and four, with four representing the 'best' type of map. For the Swedish seabed maps the scale of 1:25 000 results in the highest confidence score of three where the points are two for remote sensing coverage (almost full coverage with good multibeam and side-scan sonar coverage), one for the distinctness of class boundaries (most presented classes are distinct in the remote sensing data) and one for the amount of sampling for external validation (every or almost every presented class in the map

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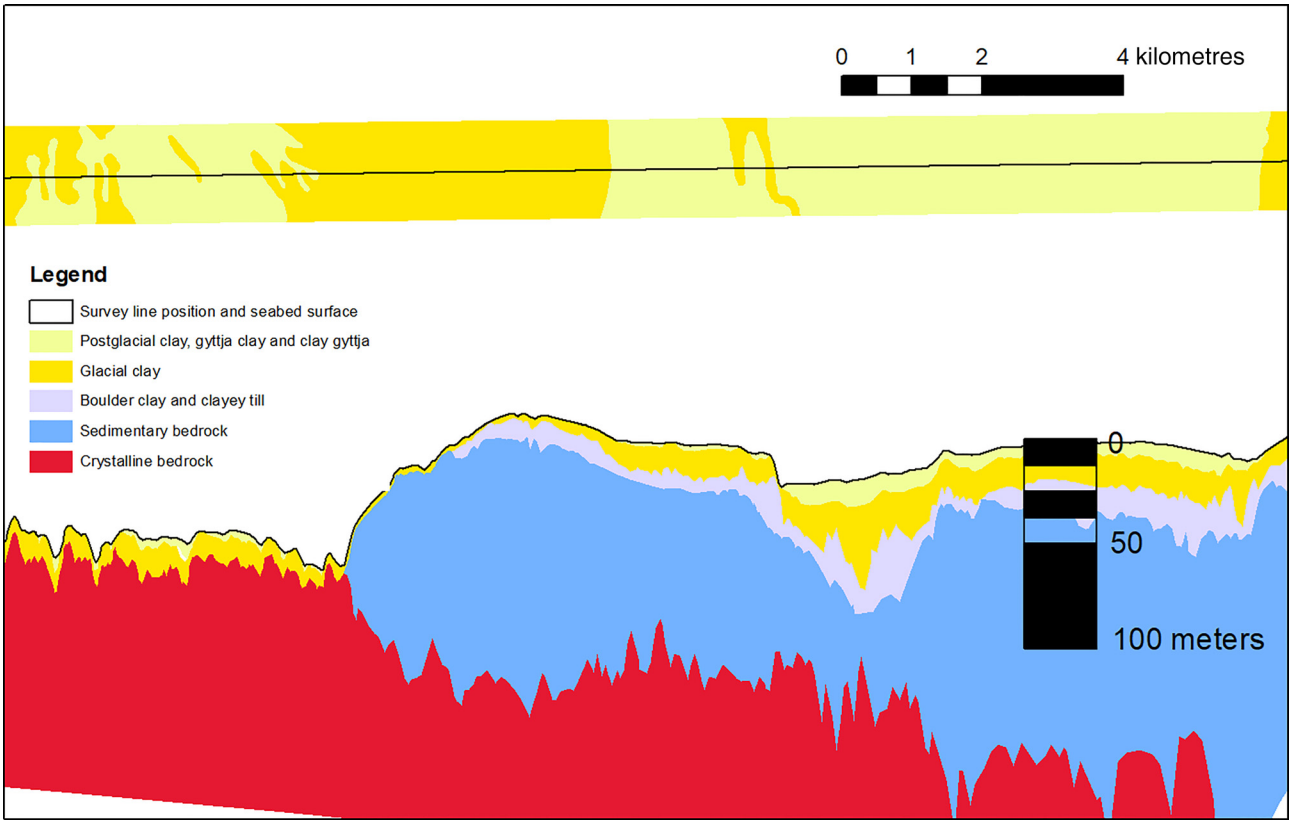

Fig. 3. Example of a vertical profile showing the stratigraphy of the seabed along the line (below) and surface geology shown in plan view (above). The horizontal distance is shown in the scale bar in the upper right corner and the vertical distance is shown in the lower right corner.

was sampled). For the scale of 1:100 000 the confidence score is three, where the points are one for the remote sensing coverage (good to moderate side-scan sonar data coverage with single beam echosounder and/or external bathymetric data), one for the distinctness of class boundaries (most presented classes are distinct in the remote sensing data) and one for the amount of sampling for external validation (many of the presented classes in the map were sampled). For the scales 1:500 000 and 1:1 000 000 the confidence score is one, where the points are zero for the remote sensing coverage (poor side-scan sonar coverage and single beam echosounder and/or external bathymetric data), zero for the distinctness of class boundaries (poor remote sensing data resulting in few or no classes being distinct in these data) and one for the amount of sampling for external validation (some of the presented classes in the map were sampled) (see Fig. 2).

Gridding

Gridding of the geological data was carried out to a horizontal resolution of 0.01° latitude and 0.02° longitude to better geographically correlate the different environmental and geotechnical parameters and resulting suitability indices with a wave climate model for the Baltic Sea, Skagerrak and Kattegat area, the WAM Cycle 4.5.1 model (Nilsson *et al.* 2019). Furthermore, the results at this resolution will be used to locate suitable pilot sites for offshore wave energy conversion and to identify favourable zones for establishing and operating future large-scale installations in Swedish seawaters.

Seabed environmental parameters

Table 1 shows six seabed environmental parameters that have been identified to be of importance for planning offshore renewable energy sites and that could be extracted from the 14 described classes in the marine geological terminology for the Swedish seabed. For five parameters, three classes have been defined and assigned a numerical weighting criterion value, except for the parameter presence of boulders, where four classes been defined. For all parameters, the weighting classes are in the order from low to high that the assigned criterion weighting values follow; that is, from one to three or from one to four. Because a low weighting class and associated low value for all parameters in Table 1 are more suitable for marine installations, the criterion weight values have been given a negative sign and the parameter has been given a multiplication factor depending on relative importance when calculating the $SI_{normalized}$ for different areas (see equations (1) and (2)).

Sediment dynamics, extent of sediment transport and size of sediment particles that are transported

The rate of particle mobilization on the seabed, extent of sediment transport, size of particles that are transported and temporarily or more permanently deposited, as well as movement of bed features, may have an influence on foundation materials, anchors and cables through physical reworking and wear (Thompson and Beasley 2012; Heath *et al.* 2017; Andersen *et al.* 2018). These factors also influence how scours will develop around foundations and cables (Whitehouse *et al.* 2011; Chen and Lam 2014; Yuan *et al.* 2017), and give an indication of whether an environment exists in which foundations and cables may stop sediment transport and cause a new substratum on the seabed that may change the habitat (Shields *et al.* 2011; Whitehouse *et al.* 2011; Petersen *et al.* 2015; Wang *et al.* 2019).

The sediment dynamics is presented in terms of the extent of movement of sediments and the dominant sizes of sediment particles that are transported. This includes the rate and size of particles that are mobilized on the seabed as well as those deposited. The degree of movement of sediments is defined and quantified into

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three normalized weighting levels where one is a low-dynamic, two is a moderate-dynamic and three is predominantly a high-dynamic seabed (see Table 1). The main sizes of the sediment particles that are transported within the areas are quantified into the three fractions defined by the international geotechnical standard SS-EN ISO 14668: Fine, Coarse and Very Coarse (see Table 1). Fine is up to the limit between silt and fine sand around 0.06 mm, Coarse is up to the limit between gravel and cobble around 60 mm and Very Coarse is coarser than that.

The sediment dynamics is, generally, estimated from the thin layer of surficial sediments when this exists. As an example, the class postglacial fine sand represents a sediment that consists of well-sorted fractions that are easily eroded and transported and is often found as a thin surface layer forming sand waves. All these features indicate a high-dynamic seabed where mainly fine- and medium-grained sand particles are transported. Another example is postglacial clay or gyttja clay, which is found in areas that have a low-exposed environment allowing fine particles and organic material to settle and deposit. This indicates a low-dynamic seabed where temporary transport of fine particles may occur.

Exposure to bottom currents

The exposure to bottom currents (i.e. strength of bottom water movement in an area) differs from sediment dynamics as sediment dynamics depends on the sediment and/or bedrock that is present in the seabed area. Movement of bottom water masses could be caused by, for example, both atmospheric pressure changes and internal and surface waves. Besides influencing materials in foundations, anchors and cables, the strength of bottom currents may affect the transmission of loads from foundations and anchors to the seafloor sediment or rock, which may affect seafloor geomaterial properties and the overall physical performance of an offshore marine renewable energy (MRE) system (Bahaj *et al.* 2007; Norske Veritas 2007; Damgaard *et al.* 2014; Heath *et al.* 2017).

The exposure to bottom currents is defined and quantified into three levels with equivalent weighting values: one, low; two moderate; three, high exposure (see Table 1). In general, glacial sediments on the seabed surface, which have been intact on the seabed for a long period of time, and/or have a washed-out surface layer with no finer fractions left, indicate a moderate- to high-exposed environment whereas young postglacial fine fraction sediments containing organic material indicate a low-exposed environment.

Heterogeneity of the seabed material

The heterogeneity of the seabed material, both horizontally and vertically, may affect technical layouts and design for foundations and anchors as well as locations of cables. Geological heterogeneity influences the geotechnical properties and the potential size of MRE arrays, which in turn may affect the uniformity, robustness or mix of different foundation–anchor systems or MRE devices that may be needed for a single site. Seabed heterogeneity for a site means that an approach involving a single foundation or anchor type may not be viable (Thompson and Beasley 2012; Barrie and Conway 2014; Heath *et al.* 2017).

The heterogeneity of the seabed material also has an effect on the diversity of biota. A heterogeneous seabed, containing hard substrates and boulders, may contain a higher diversity and abundance of species (Gogina and Zettler 2010; Gogina *et al.* 2016).

The heterogeneity of the seabed material, both horizontally and vertically in the upper 1 m of the seabed, is defined and quantified into three levels with equivalent weighting values, where one is a low, two is moderate and three is high heterogeneity. The depositional environment as well as grain size and sorting of sediments in an area affect the heterogeneity. The marine geology terminology for the sediment types that exist in an area gives information on heterogeneity of the seabed and is thus used to define the heterogeneity classes. For example, sediments that are deposited in a glacial-related environment, such as till, boulder clay and glaciofluvial material, contain a range of grain sizes, including boulders, that are unsorted and thus normally cause a moderately to highly patchy heterogeneous seabed. In contrast, sediments that are formed through redeposition after the glacial period in a non-glacial environment are normally moderately to highly sorted and thus form a low-heterogeneity seabed.

Boulders

The presence and frequency of boulders influence technical layouts and designs for foundations and anchors as well as locations of cables, and also have an effect on the diversity of biota. Seabed with a high presence of boulders offers hard substrates and may therefore contain a higher diversity and abundance of species (Gogina and Zettler 2010; Michaelis *et al.* 2019).

The presence of boulders is defined and quantified into four classes, and equivalent weighting values, according to SGF 2016 (i.e. weight per cent of the total sediment): none, 0% (weight 1); slight, <5% (weight 2); moderate, 5–20% (weight 3); high, >20% (weight 4) (Hansbo *et al.* 1984; Svenska Geotekniska Föreningen 2016). For example, sediments that are deposited in a glacial-related environment, such as till, glacial clay and glaciofluvial material, usually have a moderate to high presence of boulders whereas sediments that are formed through redeposition in a non-glacial environment normally have a zero to slight presence of boulders (e.g. Lind and Bergman 2013*a*).

Rate of accumulation of fine particles and organic material

Accumulation of fine particles and organic material influences seabed biota and how pollutants and nutrients are bound to the sediment. It has also an effect on the water content, thickness and softness of sediments, and the ratio of organic versus minerogenic material, which control sediment stability (Thompson and Beasley 2012). Also, the higher the rate of accumulation the higher the breakdown of organic material, which produces methane gas and may cause sediment instability and specific habitats.

The rates of accumulation of fine particles and organic material are defined and quantified into three levels, with equivalent weighting values: one, low; two, moderate; three, high. In general, the occurrence of young postglacial fine fraction sediments containing organic material indicates high rates, whereas coarser and/or glacial sediments indicate low rates of accumulation (e.g. Leipe *et al.* 2011; Nyberg and Bergman 2012).

Risk of dispersion of contaminants buried in sediments

There are areas in the Baltic Sea that contain contaminated sediments. There is a risk, especially during construction phases, that the contaminants buried in the sediments are released, dispersed and enter the ecosystem, causing a harmful effect (Roberts 2012).

The risk of dispersion of contaminants buried in sediments in different areas is, together with the layers of main sediment, also estimated from areas mapped as recent sedimentation and from sediment analyses, and is quantified into three levels and equivalent weighting values as low (one), moderate (two) and high (three) risks. The contaminants are normally accumulated and bound in young organic-rich sediments (e.g. Klingberg 2015*b*; Slagbrand and Klingberg 2015), and can be problematic metals such as cadmium, lead, mercury and arsenic as well as organic pollutants such as DDT, PCB, PAH and TBT (Josefsson and Apler 2019).

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Geotechnical parameters

Table 2 shows the 13 geotechnical parameters that have been identified as being of importance for planning offshore renewable energy sites and could be extracted from the 14 described classes in the marine geological terminology for the Swedish seabed. The identification of the parameters and their internal classes and assigned weightings used and considered for site, area and foundation evaluations are based on conclusions from experts with geological and geotechnical background and experience. Furthermore, sample analyses on marine sediments, both from land and seabed and from the literature (see, e.g. Larsson 2008; Nyberg and Bergman 2012; Thompson and Beasley 2012; Svenska Geotekniska Föreningen 2016; Tyréns, pers. comm., 2018), are used to define the intervals for the internal classes. Technical units and values based on results from analyses are used to define intervals for the parameters, where data are applicable, and are presented for each sediment type classified according to the marine geological terminology.

For each parameter three to five weighting classes have been defined and assigned a numerical weighting value. The weighting classes are ordered from none to very high, depending on the parameter, from one to three or from one to five. This is for all geotechnical parameters, except for excavation capacity, which is from very high (five) to very low (one), following earlier conventions. The internal weighting value for the parameter is then used together with a given criterion weight of relative importance for the parameter in obtaining an $SI_{normalized}$ for different areas. The parameter can be given a negative sign depending on whether lower or higher values for the parameter are considered as better for the planned activity.

For some of the geotechnical parameters, such as particle size, particle sorting and bulk densities, no weighting values are presented as these parameters are mostly used in the more detailed design of the installations.

Particle size

Particle size is the fundamental basis for designating mineral sediments using particle fractions to distinguish the sediment mechanical behaviour (Larsson 2008; Thompson and Beasley 2012; Svenska Geotekniska Föreningen 2016). Particle size, mainly for minerogenic coarser fractions, influences geotechnical properties such as, for example, compressibility, shear strength and hydraulic conductivity (Roy and Bhalla 2017). For sediments with finer fractions, the clay content is of importance, the geotechnical properties of which are dependent on structure and tension history rather than particle sizes.

We use the terms for the three fractions defined by the international geotechnical standard SS-EN ISO 14668 and SGF 2016: Fine, Coarse and Very Coarse sediments (Svenska Geotekniska Föreningen 2016). Fine is up to the limit between silt and fine sand around 0.06 mm, Coarse is up to the limit between gravel and cobble around 60 mm and Very Coarse is coarser than that.

Particle sorting and grading

An accumulation of sediment can also be characterized by the grain size distribution, just as particle size, particle sorting and grading influence the compressibility, shear strength and hydraulic conductivity. A poorly graded sediment will have better drainage than a well-graded sediment because there are more void spaces in poorly graded sediment. A well-graded sediment can be more compacted than a poorly graded sediment (Larsson 2008; Thompson and Beasley 2012; Svenska Geotekniska Föreningen 2016).

We define and quantify the sorting and grading into three classes according to the international geotechnical standard SS-EN ISO 14668 and SGF 2016: poorly ($Cu > 15$, $1 < CC < 3$), moderately ($6 < Cu < 15$, $CC < 1$) and well ($Cu < 6$, $Cc < 1$) (Svenska Geotekniska Föreningen 2016). Cu is the uniformity coefficient and Cc is the coefficient of gradation.

Content of organic material

The content of organic material influences water content and the ability of clay-size particles to aggregate forming an open fabric. High content of organic material may cause unusually high water contents and plasticity as well as low wet bulk densities (Keller 1982; Larsson 2008). This in turn may result in notable increases in shear strength, sensitivity and degree of apparent overconsolidation. In situations like this when there could be an excess pore pressure, sediment stability characteristics can be poor, and failure appears to take the form of a fluidized flow somewhat like quick clays on land (Booth and Dahl 1986).

We define and quantify the organic content (i.e. per cent dry matter less than 2 mm in the sediment) into four classes according to SGF 2016 and SS-EN ISO 14668 and with equivalent weighting values: none or very low, 0–2% (weight 1); low, 2–6% (weight 2); moderate, 6–20% (weight 3); high, >20% (weight 4) (Svenska Geotekniska Föreningen 2016).

Bulk density

Bulk density is an indicator of sediment compaction and porosity and can be used for calculating sediment properties per unit area. Bulk density increases with compaction and tends to increase with sediment depth. The dry bulk density of a sediment is inversely related to the porosity of the same sediment: the more pore space in a sediment the lower the bulk density value (Larsson 2008).

The bulk density is defined as the mass of many particles of the material divided by the total volume they occupy. The total volume includes particle volume, inter-particle void volume and internal pore volume. Here we estimate and quantify the bulk density below water (in tonnes m^{-3}) for different sediments according to SGI 1981 (Svenska Geotekniska Föreningen 2016). The three categories of bulk density and associated values with intervals in Table 2 are determined from sample analyses for the different sediment types classified according to the marine geological terminology, both from land and sea (e.g. Tyréns, pers. comm., 2018; Klingberg 2015*a*). These parameters are not used in the spatial analyses but are presented for use in the more detailed design of installations.

Cohesion

Cohesion is the force that holds together molecules or particles within sediments and consequently the term is used in describing shear strength within a sediment that is independent of interparticle friction.

Its definition is mainly derived from the Mohr–Coulomb failure criterion and it is used to describe the non-frictional part of the shear resistance, which is independent of the normal stress (Labuz *et al.* 2012). In general, the higher the clay and organic content, the more cohesive is the sediment (Wetzel 1990; Thompson and Beasley 2012). The sediment cohesion depends strongly on the consistency, packing and saturation condition. We define and quantify the cohesion into four classes and weighting values according to empirically obtained values for different sediments: none, 0 kPa (weight 1); low, <5 kPa (weight 2); moderate, <50 kPa (weight 3); high, >50 kPa (weight 4). The values of cohesion (in kPa) correspond to normal conditions.

Shear strength

The shear strength of a sediment or rock is a function of the stresses applied to it as well as the way in which these stresses are applied (Roy and Bhalla 2017). A knowledge of shear strength of sediments is necessary to determine the bearing capacity of foundations, the lateral pressure exerted and the stability of slopes.

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Shear strength is the magnitude of the shear stress that a sediment can sustain. The shear resistance of sediment or rock is a result of friction and interlocking of particles, and possibly cementation or bonding at particle contacts.

We estimate and quantify the shear strength for the different sediments into five categories and weighting values, according to empirically obtained Pascal values for different sediments: very low, <20 kPa (weight 1); low, <50 kPa (weight 2); moderate, 50–100 kPa (weight 3); high, >100 kPa (weight 4); very high, >10 GPa (weight 5). The undrained shear strength is used for cohesive sediments and the drained shear strength for granular sediments.

Permeability

The permeability is a measure indicating the capacity of the sediment or rock to allow fluids to pass through it. The permeability influences sediment stability and seepage (Roy and Bhalla 2017).

We estimate and quantify the permeability into three categories and weighting values, according to empirically obtained values for different sediments: low, 10^{-11}–10^{-7} m s^{-1} (weight 1); moderate, 10^{-7}–10^{-3} m s^{-1} (weight 2); high, 10^{-3}–1 m s^{-1} (weight 3).

Friction angle

The friction angle is a shear strength parameter of sediments, primarily granular material (Larsson 2008). Its definition is derived from the Mohr–Coulomb failure criterion and it is used to describe the friction shear resistance of sediments together with the normal effective stress. We estimate and quantify the friction angles into four categories and weighting values, according to empirically obtained values for different sediments: none; low, <20° (weight 1); moderate, 20–30° (weight 2); high, >30° (weight 3).

Elasticity (stiffness)

We estimate the stiffness of the sediments through the modulus of elasticity, or Young's modulus. The modulus of elasticity is a number that measures the sediment's resistance to being deformed elastically (i.e. non-permanently) when a stress is applied to it. Young's modulus describes tensile elasticity or the tendency of the sediment to deform along an axis when opposing forces are applied along that axis; it is defined as the ratio of tensile stress to tensile strain (Anon. 2017). In general, the soil stiffness and elastic modulus depend on the consistency and packing (density) of the sediment. We define and quantify the sediments into four categories and weighting values, according to empirically obtained values for different sediments when the sediments are medium (normal) in consistency and packing: none; low, <10 MPa (weight 1); moderate, 10–30 MPa (weight 2); high, >30 MPa (weight 3).

Vertical bearing capacity

The vertical bearing capacity, which gives information on the ability of a sediment or rock to hold up loads applied to the seabed, is of importance when offshore installations are secured to the seabed by, for example, foundations (Thompson and Beasley 2012). The bearing capacity is defined as the load per unit area that will just cause a failure in the supporting sediment or rock. The allowable bearing capacity is the load per unit area that the sediment or rock is able to support without unsafe movement. We define and quantify the bearing capacity into five levels and weighting values, according to empirically obtained values for different sediments: very low, <25 kN m^{-2} (weight 1); low, <50 kN m^{-2} (weight 2); moderate, 50–100 kN m^{-2} (weight 3); high, 100–300 kN m^{-2} (weight 4); very high, >300 kN m^{-2} (weight 5). For the Swedish seabed, low is, in geological terminology, sediments such as soft postglacial clay, gyttja clay or clay gyttja thicker than *c.* 1 m, and high is crystalline bedrock in the seabed surface (see Table 2).

Excavation capacity

The excavation capacity, which is defined as the sediment's ability to be excavated underwater, is of importance, together with sediment suction ability, when installations are secured by anchors to be embedded in the sediments (Svenska Geotekniska Föreningen 2016). Excavation capacity is also of importance when laying cables (e.g. for cable routing). The excavation capacity is defined and quantified into five categories and weighting values: very high (weight 1); high (weight 2); moderate (weight 3); low (weight 4); very low (weight 5), based on Svenska Geotekniska Föreningen (2016). This system is developed through results from geotechnical investigations where high means a low resistance in excavation and a high loading capacity for the material, whereas low means a high resistance in excavation and a low loading capacity. For the Swedish seabed, sediment such as soft postglacial clay, gyttja clay or clay gyttja thicker than *c.* 1 m has a high excavation capacity and crystalline bedrock directly on the seabed surface has a low excavation capacity (see Table 2).

Installation techniques

The suitability and performance in securing constructions with eight different installation techniques (i.e. type of foundation and anchor) for each of the 14 classes in the marine geology terminology are defined and quantified into three levels as not well, moderate and well for different areas (see Table 3). The levels of suitability and performance are from Thompson and Beasley (2012). Heath *et al.* (2017) and Tyréns pers. comm. (2018). These translations are to be used for general discussions and visual or GIS analysis on installation techniques in different areas. As two examples, the suitability of different areas for two common relatively uncomplicated and low-cost techniques, gravity-based and suction caisson type foundations, compared with other techniques in securing wave energy conversion plants respectively, are shown in Figures 4 and 5. The suitability of gravity-based and/or suction caisson foundations in different areas is further discussed and analysed in this paper when environmental parameters also are considered in finding suitable areas and installation techniques.

Results and discussion

The parameters presented here that can be derived from the existing marine geological information (see Tables 1 and 2), together with water depths and associated bathymetric heterogeneity and slope, give a first overview of an area's seabed environmental conditions and general geotechnical properties. The parameters give information on suitability and overview designs for offshore renewable energy installations. As an example, in finding suitable cable routes, as well as areas, planning size and design for a wave energy conversion plant on the Swedish seabed involving point absorbers, with gravity foundations, which is a common technique for securing wave energy arrays, we use equations (1) and (2) combining seabed environmental and geotechnical parameters to obtain $SI_{normalized}$ (see Tables 1, 2 and 4 and Figs 6a–g and 7a–d). In the first step of the example, we use the six seabed environmental parameters that have an impact on both environmental and geotechnical conditions (see Table 1 and Fig. 6a–f) to find the areas on the Swedish seabed that are suitable from a seabed environmental and general geotechnical point of view. We give the parameters sediment dynamics, exposure to bottom currents, heterogeneity of seabed material, presence of boulders, rate of accumulation of fine particles and risk of dispersion of contaminants buried in sediments a negative weight of unity (see Table 4) because of the low internal weighting class and associated low value for these parameters, which indicates that they are more suitable for marine installations from an environmental point of view (see Table 1). We also give the parameters the same criterion weight, a multiplication

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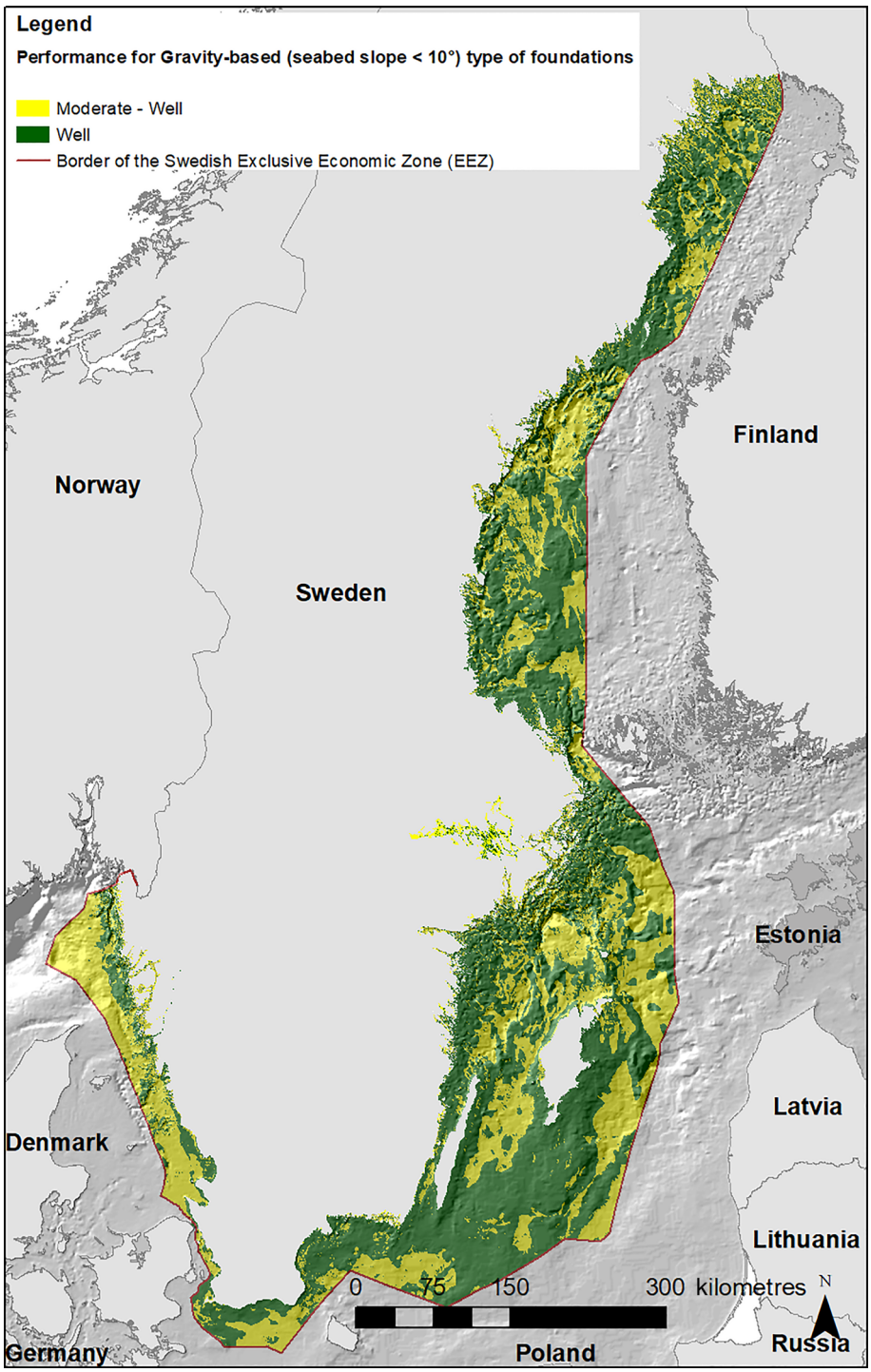

Fig. 4. The suitability of different areas for a gravity-based foundation solution in securing installations, based on translation from the marine geological terminology for the sediment types.

factor of unity, as we consider that these environmental parameters are equally important in relation to offshore energy installation in this overview analysis of the whole Swedish seabed because of the size and diverse conditions of this large area. The parameters can, however, be given different weights and importance depending on, for example, size, geological conditions, location, sensitivity and level of details for the areas to be analysed. For environmental and geotechnical reasons, areas with low sediment dynamics and low exposure to bottom currents are considered as more suitable, as they may exhibit a lower risk of foundation and cable damage or wear and a reduced occurrence of scours in the seabed. Scours in the seabed may decrease stability (Heath *et al.* 2017). Installations in such areas may also have a lower risk of changing sediment transport patterns. A low presence of boulders and a low heterogeneity of seabed material decrease the probability of hard substrates and thus the number and diversity of species as well as number of individuals. These areas are thus considered as being more environmentally suitable as there will be less disturbance of marine biota. Also, a high presence of boulders and a high heterogeneity of the seabed material may be less suitable through impacts on array layouts, design and performance owing to, for example, the need to use several types of foundations and anchors; also, such seabed conditions will pose a challenge in finding safe cable corridors (Barrie and Conway 2014; Heath *et al.* 2017). Areas with a lower rate of accumulation of fine particles and a lower risk of dispersion of contaminants buried in sediments are considered as more suitable, as they will exhibit a decreased risk of turbidity and release of contaminants into the ecosystem during construction phases. Also, areas with sediments that have a lower content of organic material are considered as more suitable, as these sediments may have a lower gas and water content, which will reduce the risk of a weaker seabed.

The $SI_{normalized}$ results from the weightings (Fig. 6g) of the six environmental parameters (Table 4 and Fig. 6a–f) give indications

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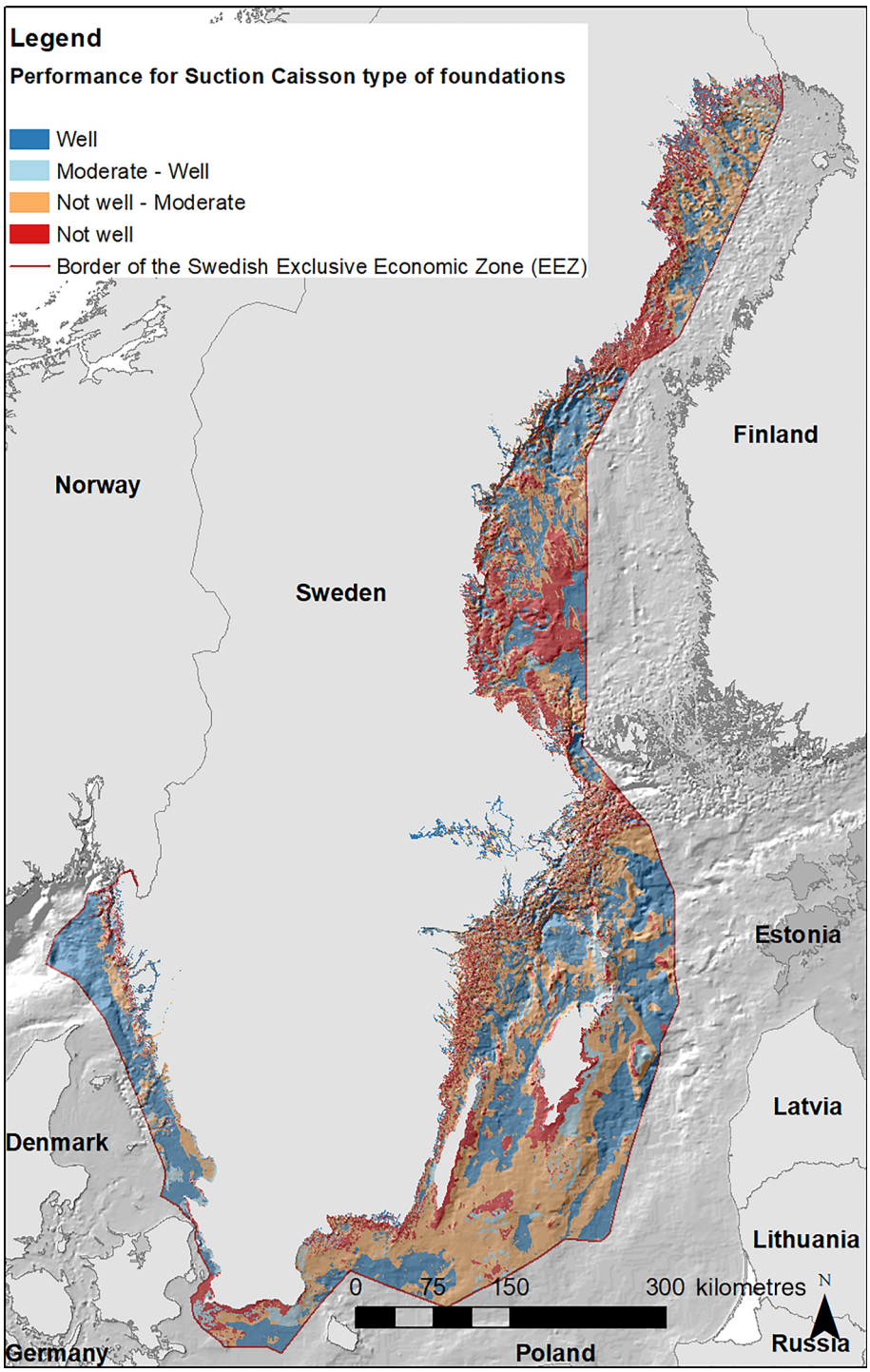

Fig. 5. The suitability of different areas for a suction caisson foundation solution in securing installations, based on translation from the marine geological terminology for the sediment types.

of where the environmental and general geotechnical properties of the seabed may be suitable for a wave energy plant. The higher the score the more suitable the location.

The next step, in this example, is to investigate the types of sediments and seabed in which gravity foundations are suitable for use to secure the wave energy absorbers. Using gravity foundations in securing wave energy absorbers to the seabed is a relatively uncomplicated and low-cost technique compared with other techniques. In this case, we use the geotechnical parameters organic content, excavation capacity, shear strength and vertical bearing capacity (see Table 4 and Figure 7a–c). We give organic content a negative criterion weight of unity because higher internal weightings for this parameter indicate poorer suitability. A higher organic content indicates high water content, high plasticity and low wet bulk density, which may result in weaker and looser sediments (Thompson and Beasley 2012) as well as landslide risks (Heath *et al.* 2017). Shear strength, vertical bearing capacity and excavation capacity are given positive weightings of unity, as high internal weightings for these parameters indicate better suitability. High shear strength, high vertical bearing capacity and low (a high weighting value) excavation capacity of the seabed are suitable factors, as they indicate a high loading capacity and resistance of forces that are downward and upward as well as horizontal (Heath *et al.* 2017). We also give the parameters the same criterion weight, a multiplication factor of unity, as we consider that these geotechnical parameters are equally important in relation to offshore energy installation in this overview analysis of the whole Swedish seabed.

The third step is to find the suitability for use of gravity foundations in the environment considering different areas. We therefore use the four geotechnical parameters with weightings (Table 4 and Fig. 7a–c) in combination with the six environmental

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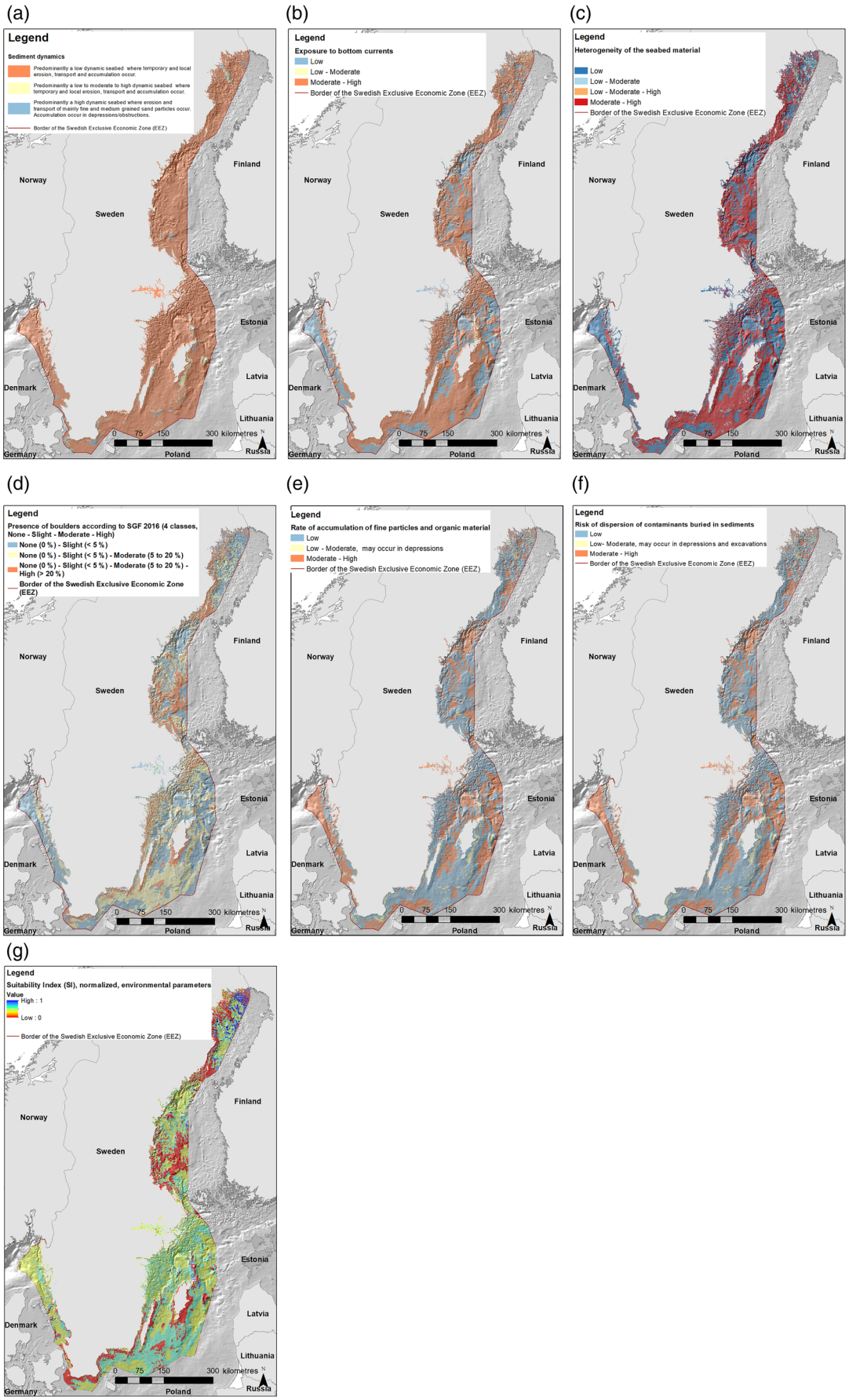

Fig. 6. (**a**) Sediment dynamics, extent of sediment transport and size of particles that are transported, (**b**) exposure to bottom currents, (**c**) heterogeneity of the seabed material, (**d**) presence of boulders, (**e**) rate of accumulation and (**f**) risk of dispersion of contaminants, based on translation from the marine geological terminology for the sediment types. (**g**) The normalized Suitability Index (SI), which is the sum of the products derived from the factors in the considered seabed environmental parameters given the weights as in Table 4. The higher the score, the more suitable for a wave energy conversion plant from a seabed environmental point of view.

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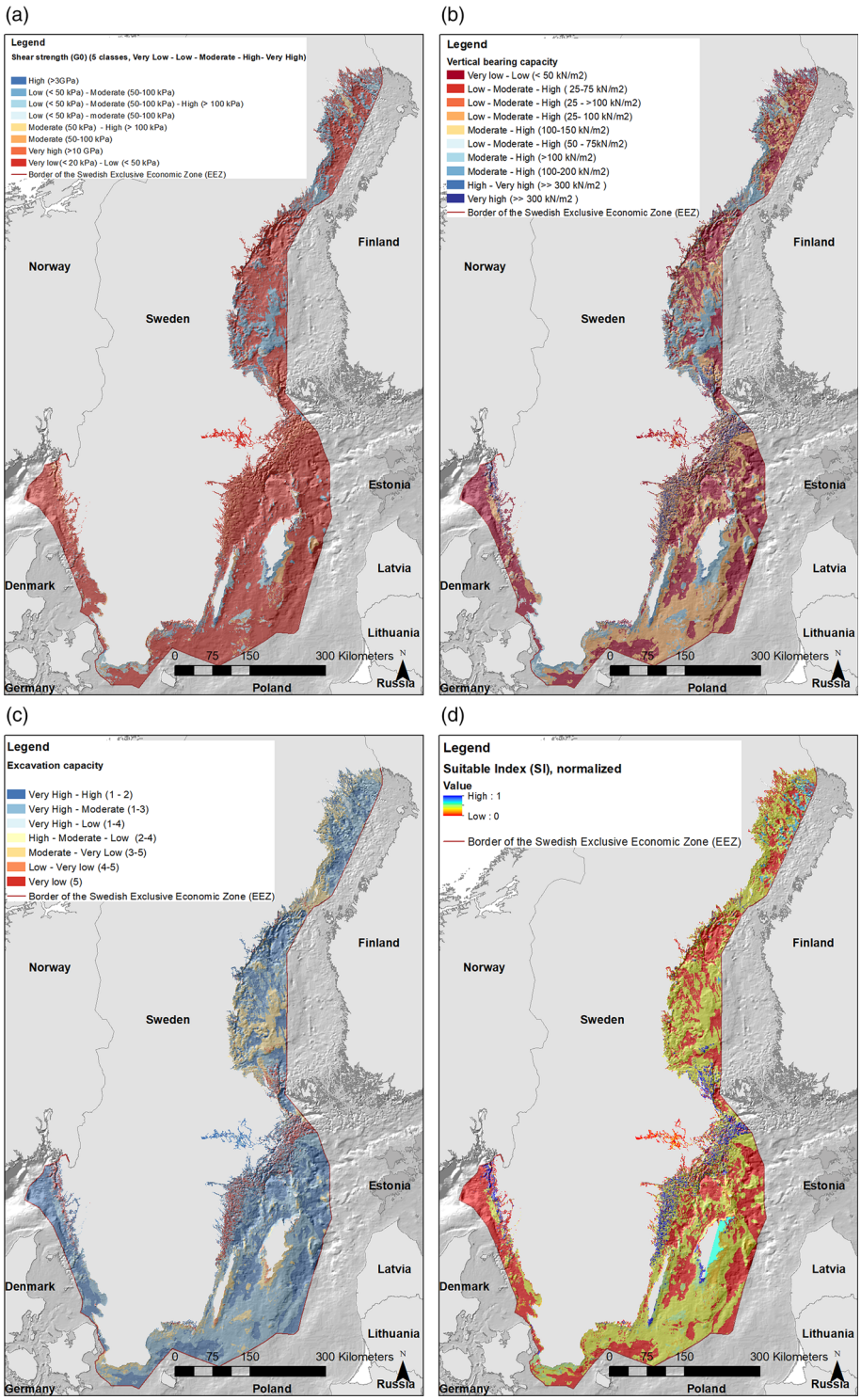

Fig. 7. (**a**) Shear strength, (**b**) vertical bearing capacity and (**c**) excavation capacity, based on translation from the marine geological terminology for the sediment types. (**d**) The normalized Suitability Index (SI), which is the sum of the products derived from the factors in the considered seabed environmental and geotechnical parameters given the weights as in Table 4. The higher the score, the more suitable, from both an environmental and geotechnical point of view, for a wave energy plant with gravity foundations.

parameters with weightings (Table 4 and Fig. 6a–f), thus basically combining the resulting layers shown in Figures 4 and 6g. The $SI_{normalized}$ results from these 10 considered parameters are shown in Figure 7d. This resulting layer can thus be used to locate the areas that are most suitable for a gravity-foundation wave farm from an environmental and geotechnical point of view derived from the parameters extracted from the geological information. In general, a higher score (Fig. 7d) represents a seabed that exhibits a higher stability owing to higher shear strength and vertical bearing capacity. The seabed also exhibits lower gas and water contents, plasticity and wet bulk densities, which result in less loose sediments. In addition, the area exhibits a lower presence of boulders, less geological heterogeneity, lower sediment dynamics as well as fewer contaminants and a lower associated risk of releasing them into the ecosystem. All of these characteristics of the seabed are considered as being suitable, from a safe, environmental-friendly and economic point of view, when planning, designing and securing a wavefarm to the seabed using gravity foundations.

Using this information on SI for different areas together with knowledge of water depths and seabed slope to exclude areas that are too deep and have too high a slope (e.g. more than 10°) will improve the spatial information on where the use of gravity foundations is suitable for a wave energy plant.

Information on vertical and horizontal changes in sediment composition and associated environmental and geotechnical parameters within the high-SI presumptive areas is also of importance and should be considered when establishing the eventual optimal sites and technical solutions. Expected

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Table 4. *The considered parameters and their criterion weights, which are multiplied by the numerical value for defined classes in each parameter*

Seabed environmental parameters						Geotechnical parameters			
Sediment dynamics, extent of sediment transport and size of sediment particles transported	Exposure to bottom currents	Heterogeneity of seabed material	Presence of boulders	Rate of accumulation of fine particles and organic material	Risk of dispersion of contaminants buried in sediments	Content of organic material	Shear strength	Vertical bearing capacity	Excavation capacity
−1	−1	−1	−1	−1	−1	−1	1	1	−1

The normalized sum of the products derived from these factors gives the SI for different areas intended for offshore installations (in this case wave energy conversion plants with gravity foundations).

stratigraphy for an area could be developed by using a combination of thin surface layers, dominant material in the upper 1 m and knowledge of the geological history and bathymetry (see Fig. 3).

More parameters can be involved in the weighting process and the parameters can be given other weights depending on purpose and installation technique, such as suction caissons. For instance, knowledge of the geotechnical properties particle size, sorting and grading, bulk density, consolidation, cohesion, permeability and stiffness of the seabed material is important when analysing the response of the seabed to the type of loading that the installation's mooring and/or foundation system will experience (e.g. static, cyclic or impulse; Heath *et al.* 2017) as well as in planning, designing and installing suction-assisted foundations and anchors (Akeme *et al.* 2018). The parameters may also be used when analysing the seabed's response to, for example, compaction, vibration and scouring during installation. Another important geo-risk to consider is landslides, which could be triggered both during and after the installation.

Suitable areas for securing a wave farm to the seabed with suction caissons have the same environmental parameters as for gravity foundations; that is, low presence of boulders, low geological heterogeneity and low sediment dynamics, as well as low presence of contaminants and associated risk of releasing them into the ecosystem (Fig. 6g), although the geotechnical parameters are different. The seabed should consist of, for example, fine, sorted particles and have a low bulk density, consolidation and stiffness, as well as moderate to high cohesion and permeability.

When investigating whether it is better to use suction caisson or gravity foundations in the areas that are suitable from an environmental point of view, it is advantageous to use GIS because of its applicability in immediately generating visual information on geographical maps. For example, comparing Figs 4, 5 and 6g with each other and including information on, for example, slope and water depths may give a good fast overview to locate suitable areas for the different installation techniques. In general, looking just at seabed properties, gravity-based foundations are applicable with a well to good performance for the whole Swedish seabed, displaying a higher suitability closer to shore and shallower areas in the Baltic proper, Bothnian Sea and Bothnian Bay compared with the Kattegat and Skagerrak (Fig. 3). The suitability of suction caisson does not have as high a geographical coverage, except for areas further from shore in the Kattegat and Skagerrak, but this method is suitable in deeper areas in the Baltic proper, Bothnian Sea and Bothnian Bay (Fig. 4). Some areas close to shore and shallower areas further offshore in the Baltic proper, Bothnian Sea and Bothnian Bay are not suitable at all for suction caissons. The two different techniques can perform moderately to well in the same areas, but each performs, in general, well in areas where the other technique does not.

Other parameters, such as an area's resource potential, distance to land and network stations, being a Natura 2000 area, shipping and fishing density, ice occurrence, etc. can, of course, also be considered, in finding optimal sites for offshore renewable energy (see Strömstedt *et al.* 2017).

Many of the quantifications and values for different parameters presented here are based on experience with known seabed conditions, analysed geotechnical values and installations already built. As the presumptive values are based only on the classification of the 14 geological categories, they are not fully reliable. These values do not consider factors affecting the seabed such as, for example, the shape, width and depth of footing of a structure. or the effect from seawater pressure on strength and compressibility of the sediment. Generally, the values are conservative and can be used for preliminary planning and overview design of foundations or structures. A statistical validation of the reclassification is not presented because too few data records for the parameters exist to obtain a robust and reliable analysis for the whole Swedish area. A statistical validation analysis should thus be carried out when more

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data, samples and analyses on the parameters are retrieved. Also, measured or modelled data on, for example, sedimentation rates, sediment transport, exposure and bottom currents should be included and compared when such data are available. It is thus recommended that further investigations are performed on sediment and environmental data *in situ* or in the laboratory or through models.

Conclusion

Six seabed environmental and 13 geotechnical parameters are identified, categorized, quantified and mapped from available marine geological information. In addition, the performance of four types of foundations and four types of anchors for different seabed types and areas is presented. The identified parameters can be weighted and summed and used together with other parameters, such as resource potential, ecosystem sensitivity, ice occurrence and human activities, to find the sites that are most environmentally sustainable and technically safe for offshore renewable energy installations. The quantifications and technical values for each parameter can be used in both the overview and detailed analysis of site selections. A method is presented and used as an example in selecting the most suitable locations from geological information for wave energy conversion within the Swedish EEZ. On the basis of an environmental and general geotechnical point of view, areas are selected where the seabed exhibits a lower presence of boulders, less geological heterogeneity and lower sediment dynamics, as well as fewer contaminants and associated risk of releasing them into the ecosystem. Together with this information, areas suitable for securing wave energy absorbers with gravity foundations and/or suction caissons are presented. Suitable areas for gravity foundations have a seabed that exhibits a higher stability owing to higher shear strength and vertical bearing capacity. The seabed also has lower gas and water contents, plasticity and wet bulk densities, which result in less loose sediments. Areas suitable for suction caissons have a seabed that consists of fine, sorted particles and a low bulk density, consolidation and stiffness, as well as moderate to high cohesion and permeability.

The resolution of the spatial information presented here and provided publicly by SGU can be used in the overview marine spatial planning, whereas datasets that are of a higher resolution and are more site specific, from both *in situ* field and laboratory investigations, should be used in the final detailed planning and design of the installation.

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Author contributions **JN**: conceptualization (lead), data curation (lead), formal analysis (lead), investigation (lead), methodology (lead), project administration (supporting), visualization (lead), writing – original draft (lead), writing – review & editing (lead); **LZ-S**: data curation (supporting), formal analysis (supporting), funding acquisition (supporting), project administration (supporting), resources (supporting), writing – original draft (supporting), writing – review & editing (supporting); **ES**: conceptualization (supporting), data curation (supporting), formal analysis (supporting), funding acquisition (lead), project administration (lead), writing – review & editing (supporting)

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Data availability The open geological information is available at http://www.sgu.se. Some of the datasets generated and analysed during the current study are not publicly available owing to specific restrictions, but may be available from the Geological Survey of Sweden, upon reasonable request.

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