Coastal vulnerability mapping of the fjords in the Romsdal area, Norway using geoinformatics

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1. Introduction

In the light of climate change, it has become of critical importance to monitor Critical Water Zones (Bianchi et al., 2020). Among these zones, fjords, as geomorphological features located mainly at high latitudes, require special attention. Fjords have a distinct transverse and long profile, referred to as a U-shape (*Encyclopedia of geomorphology*, 2004). In these geomorphs, solid precipitation makes its way to the sea by eroding the bed and, as it flows, creates a rocky channel, much like liquid precipitation in temperate countries. In those formations, erosion rates are variant, characterized by low rates at the highest levels of the formations ranging from 0.2 to 1 mm per, as opposed to the lower levels where it increases significantly, on the order of 1 cm per year.

The importance of fjords is undeniable great both for the areas surrounding them and for the wider areas indirectly affected by them. These glacier-engraved features further represent the transition from terrestrial to marine environments and typically include sediments that highlight climatic and environmental changes over time (Howe et al., 2010)). Furthermore, it is well documented that submarine mass movements occur frequently in fjords and may be associated with a wide range of movement mechanisms. Mass transfer deposits (MTDs) associated with such processes may account for more than 70% of fjord basin fills (Bellwald et al., 2016). However, as mass movements have been identified over time periods characterized by changing sedimentation rates, sediment supply alone cannot explain the observed mass movement clusters (Schultze et al., 2022). Given the dynamic nature of those formations and their importance for climate and local communities, it has become of critical importance to adopt labor and cost-efficient method to assess manmade or natural changes imposed on this habitat.

To this end, Earth Observation (EO) technologies pose as an ideal solution. Satellite missions, especially multi-spectral missions, are the most common source of data for land cover classification due to their high temporal resolution and suitability for efficient computer processing (Radočaj et al., 2020). Amongst the existing EO programs, Landsat mission is considered one of the most important with over 50 years archive (Arévalo et al., 2023), allowing quantification of impacts, while providing the information necessary to understand long-term consequences and understanding the long-term evolution of fjords (Wulder et al., 2022). The results of continuous fjord monitoring can form the basis for formulating policies and regulations for appropriate protection and development of the resources and specificity of the region, and for planning the development of local industry.

A particularly promising methodology in evaluating the vulnerability of Arctic coasts is a multivariate geospatial index, the so-called Coastal Vulnerability Index (CVI). CVI expresses the degree of vulnerability of a coastline by taking into consideration different physical factors such as geomorphology, oceanographic factors (sea level rise, wave height, and tidal range), and shoreline retreat or advance to estimate the degree of vulnerability of a coastal area. Coupling CVI with advanced geoinformation tools (Tsatsaris et al., 2021), including EO imagery, unmanned aerial vehicles that enable data collection from a safe distance. Classifying the observed area into several generalized land cover categories creates a universal basis for spatial planning and monitoring changes in the environment (Faust et al., 2017). This index is important for identifying coastal segments and infrastructures as well as other activities that are essentially susceptible to the risk posed by different physical factors (Kovaleva et al., 2022). CVI has been extensively applied to various environmental settings, but its application in the Arctic is yet underexplored with only a limited number of studies existing (Jaskólski et al., 2017; Toumasi et al., 2024).

The present study aims to assess the coastal vulnerability of a fjord system located in Norway using geoinformatics. This case study highlights the application of advanced technologies in understanding and managing coastal dynamics, particularly in the context of climate change. By leveraging geospatial tools and datasets, the research provides insights into the risks faced by Arctic coastal regions, offering valuable information for sustainable management and adaptation strategies.

2. Experimental set-up

2.1. Study Area

As the experimental site of this case study, a fjord located in western Norway, in Møre og Romsdal County (Møre og Romsda) has been selected. Norway has a total area of 385,207 square kilometres and a population of 5,425,270 inhabitants (Eurostat, 2022). The country has a long eastern border with Sweden and also shares borders with Finland, Russia and Denmark. Norway has an extensive coastline, in the North Atlantic Ocean and the Barents Sea. The examined county is consisted of three districts of Sunnmøre, Romsdal and Nordmøre, and with population close to 266 thousand people, according to the latest census of 2022 (“Eurostat,” n.d.). To better organize the study area will be divided into three different points (Figure 1). These consist of the main branch of the system, which is Storfjiorden and connects the coastal area and by extension the sea to the mainland. It then moves on to the secondary branch, in which Storfjiorden, Sunnylvsfjiorden and finally ends in Geirangerfjiorden. These three parts are of interest both for the physical and anthropo-geographical features that define the whole.

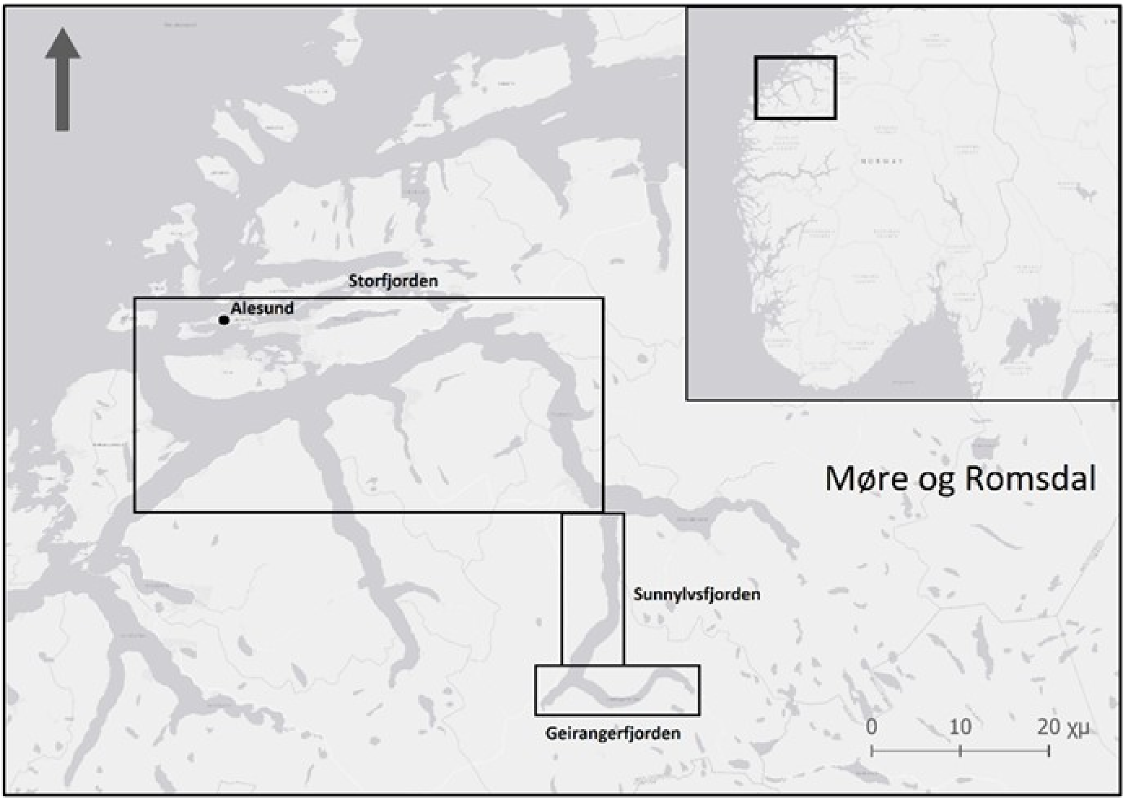

Figure 1: *The geographical location of the examined fjord system. The experimental site is split into three sub-districts the Storfjorden, Sunnylvsfjorden and Geirangerfjorden.*

2.2. Datasets

CVI consists of a multivariate index that considers several factors that can influence the vulnerability degree. For the purposes of this study, six variables linked to natural characteristics and physical processes (geomorphology, slope, shoreline change, oceanographic conditions) were considered in reflecting the coastal vulnerability of the study area. Below, an analytical description of each variable used for the estimation of CVI is presented. Different analysis systems were therefore used to retrieve these data, and thus different tools were used to produce results.

2.2.1. Geospatial data

Satellite data from Landsat sensor were collected by the USGS are LC09_L2SP_201016_20220920_20230328_02_T1 and the similar framing data for the year 2022. The LT05_L2SP_201016_20100927_20200823_02_T1 and its counterparts for the year 2010. The latest for satellite data is the LT05_L2SP_201016_20000307_20200907_02_T2 for the year 2000. Initially, the date chosen is September, a period when there is no significant cloud cover in the available image and even more importantly in the area of interest. At the same time, the percentage that was set as the cloud cover threshold is 10%, which limits images that are likely to have clouds over the fjord and prevent the smooth process of preparing the paper. In addition, Copernicus Digital Elevation Model (European Space Agency (2024)., n.d.), which provides elevation information at 30m spatial resolution, was selected to determine the geomorphs DEM and slope rate of the coastal area.

2.2.2. Oceanographic data

Regarding the representation of the oceanographic conditions of the area, three parameters were taken into consideration during the CVI estimation. Those consist of (i) the relative sea level change of the examined area expressed in units of millimeters per year (mm/yr), (ii) the mean tide range expressed in meters, and (iii) the mean wave height conditions expressed also in meters. Data about the relative sea level rise and mean tidal range between 2010 and 2020 were obtained by a tide gauge station installed near Alesund, available through the Norwegian Hydrographic Services Mapping Authority database (api.sehavniva.no, accessed on 10 October 2024). The data recorded by the tidal gauge was considered representative for the whole examined area. Regarding mean wave height, a value of 1.0 m was selected based on the physiographical characteristics of the wider area and in accordance with other similar studies which took place in the wider geographical area. In combination with the wave height, equally important is the isostasy that characterises the area and alters the influence of the wave height. This isostasy, according to the model "NKG2016LU_abs" and the website containing the wave data (Kartverket), is at 2.1 mm. Regarding, mean sea level the resulting values were -1.2 cm for 2010 and 4.7 cm for 2020. Considering the isostasy from the model "NKG2016LU_abs", 2.1 mm are subtracted from these values.

3. Methodology

3.1. Data pre-processing

Prior to estimating coastal vulnerability, following data acquisition, it is imperative to prepare the data through pre-processing to ensure its usefulness for producing reliable results. All processing steps implemented herein were performed using ENVI 5.3 software.

3.1.1. Geomorphology

The process of the project starts with the transfer of the DEM data from OpenTopography in the GIS program. In parallel, to further validate the geomorphs produced by the DEM classification, high resolution stereo imagery was used through ("Norge i Bilder," n.d.) (https://norgeibilder.no/). By observing the area in 3D, it was possible to validate the DEM-derived geomorphs and make adjustments where needed.

3.1.2. Shorelines accretion/erosion rates

To estimate shoreline accretion and erosion rates, the coast from the two Landsat images were extracted using a binary supervised classification. Spectral signatures from land and water were recorded, and raster-to-vector conversion was performed on the classified images using ENVI 5.3 software to extract the shorelines of the study area.

The Maximum Likelihood Classification (MLC) method was identified as the most suitable for performing the binary classification. Statistically robust, this method is grounded in Bayes' theorem, which calculates marginal distributions and internal correlations under the assumption of multivariate normality in N-dimensional Euclidean space (Gevana et al., 2015). The classification accuracy was validated using metrics such as overall accuracy and Cohen's Kappa coefficient. The results demonstrated a high degree of reliability, with an overall accuracy of 99.65% and a Kappa coefficient of 0.99, confirming the method's effectiveness in evaluating satellite imagery.

Subsequently, after extracting the coastline from the classified imagery using standard GIS procedures, the Digital Shoreline Analysis System (DSAS) tool was employed to calculate the shoreline displacement rate. DSAS, an Esri ArcGIS extension developed by the United States Geological Survey (USGS), enables the calculation of shoreline change rates using shorelines from different dates. This tool has significantly advanced shoreline change analysis globally. DSAS generates cross sections, or transects, perpendicular to a user-defined baseline along the coast. These transects are modelled from a theoretical baseline located at a set distance from the most recent shoreline. The tool then calculates the intersection points of each shoreline with the cross sections, enabling the computation of shoreline change rates (Sunny et al., 2022).

3.3 Estimating Coastal Vulnerability Index

After pre-processing the CVI factors into the appropriate format, the vulnerability degree of each factor was classified into 5 categories using the ranking suggested by (Jaskólski et al., 2017) which is being presented into Table 1.

Table 1. The Coastal Vulnerability Index (CVI) ranks variables into five categories, each representing a different level of vulnerability, ranging from very low to very high as suggested by (Jaskólski et al., 2017)

Vulnerability Ranking	Very Low	Low	Moderate	High	Very High
Parameter	1	2	3	4	5
Geomorphology	Rocky, cliffed coast, fjords, fiards	Medium cliffs, indented coasts	Low cliffs, glacial drift, alluvial plains	Cobble beaches, estuary	Barrier beaches, sand beaches, deltas, sand spits
Coastal slope (°)	>10.0	6.0–10.0	3.1–6.0	1.0–3.0	<1.0
Relative sea level change (mm/yr)	<1.8	1.8–2.5	2.5–2.95	2.95–3.16	>3.16
Shoreline erosion/accretion (m/yr)	>2.0	1.0–2.0	(−1.0)–(+1.0)	(−1.1)–(−2.0)	<−2.0
Mean tide range (m)	>6.0	4.1–6.0	2.0–4.0	1.0–1.9	<1.0
Mean wave height (m)	<0.55	0.55–0.85	0.85–1.05	1.05–1.25	>1.25

After assigning to each one of CVI parameters its vulnerability ranking, CVI was estimated using the following formula (equation 1):

$$\boldsymbol{CVI} = \sqrt{\frac{\boldsymbol{a * b * c * d * e * f}}{\boldsymbol{6}}} \qquad (\boldsymbol{equation\ 1})$$

where a = geomorphology, b = shoreline change rates, c = coastal slope, d = relative sea level rate, e = mean significant wave height, and f = mean tidal range.

4. Results

The resulted CVI map of the experimental site is presented in Figure 2. The resulted map showcased low to moderate risk throughout the examined area. Coast segments closer to the fiord entrance, belonging to the Storfjiorden segment, showcased higher degrees of vulnerability. On the contrary, coasts that belong to the Sunnylvsfjiorden and Geirangerfjiorden segments depict in general a lower degree of vulnerability.

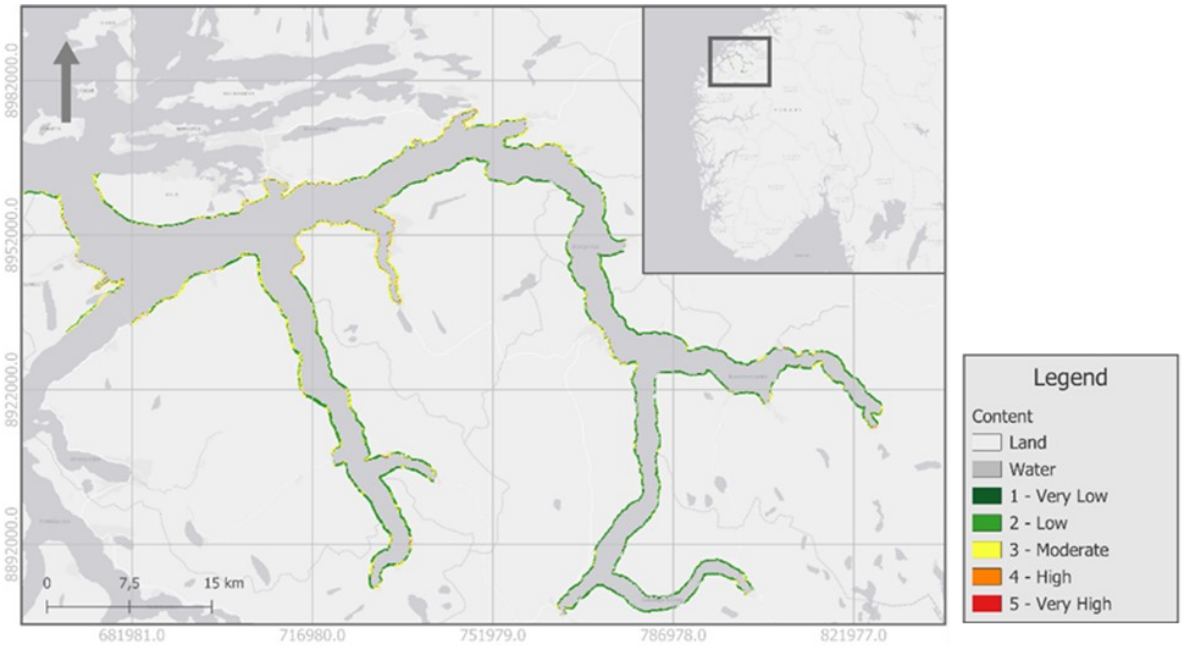

Figure 2: *The coastal vulnerability index map.*

The resulting graph shows that most of the study area is characterized by very low and low risk, which indicates the absence of changes in the places that make up these classes. Added to this is the moderate hazard, in which the parts that make up this class do not show significant alteration in their relief. Finally, the areas of high and very high risk make up only 8% of the area, indicating that there are areas that require observation and intervention in a few cases. From these results, it appears that the study area is mostly covered by areas that are not at immediate risk.

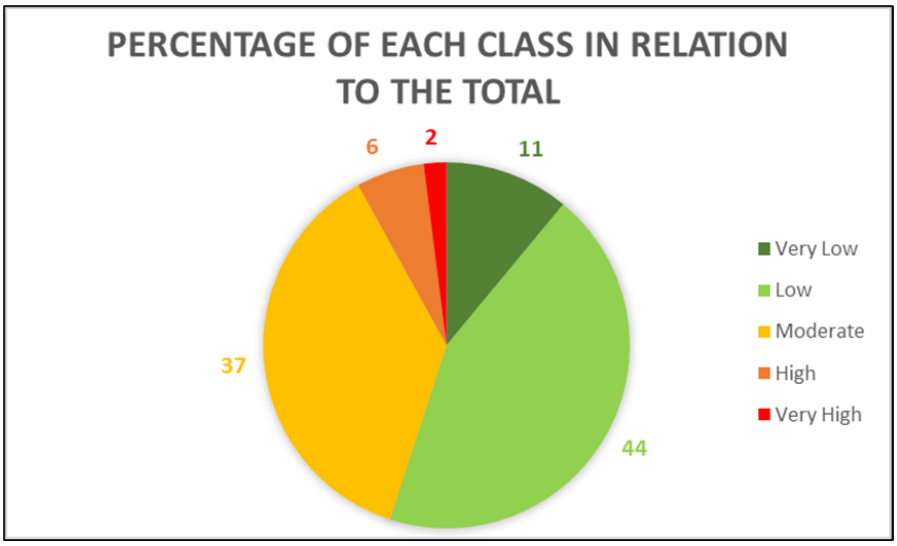

Figure 3: *Graph for the percentage (%) of each class within the study area*

In terms of each individual factor of CVI, the map resulting from the pre-processing and data processing presents a visualization of the geomorphological risk, dividing it into five classes in ascending order of hazard, from least to most dangerous. According to the generated image (Figure 4, a), most of the fjord system is characterized by low hazard (class 2), with the northern parts predominantly exhibiting moderate hazard (class 3). A few regions in the southern and eastern parts of the system are classified as very low hazard (class 1). By analyzing the image of the area (Figure 4, b), which has been broken into smaller sections for better interpretation, areas with high (class 4) to very high (class 5) coastal slope risk indices are identified. These high-risk areas are typically located in beach regions, where hollow formations transition towards lowland areas. Conversely, areas with minimal erosion exhibit indices ranging from very low to low, indicating a reduced coastal slope risk. These variations are associated with a very low risk level for the entire study area. Data obtained from DSAS were further simplified into a single set of values (Figure 4, d), highlighting considerable differences in shoreline variation hazards. Moderate risk values dominate, suggesting that the area has experienced several geomorphological changes over time. Comparing the mean tidal range with changes in sea surface height (Figure 4, c), both similarities and differences are evident. In terms of similarities, the values between points show minimal deviations, resulting in consistent visualization of data along the coastline. However, the mean tidal range exhibits exclusively high values, in contrast to the low relative sea level variations. Regarding wave dynamics, the mean wave height is limited to high hazard values, like the mean tidal range (Figure 4, e). These findings suggest that the fjord system operates largely autonomously from the open sea due to minimal internal variations, whereas the open sea demonstrates significant changes driven by weather conditions.

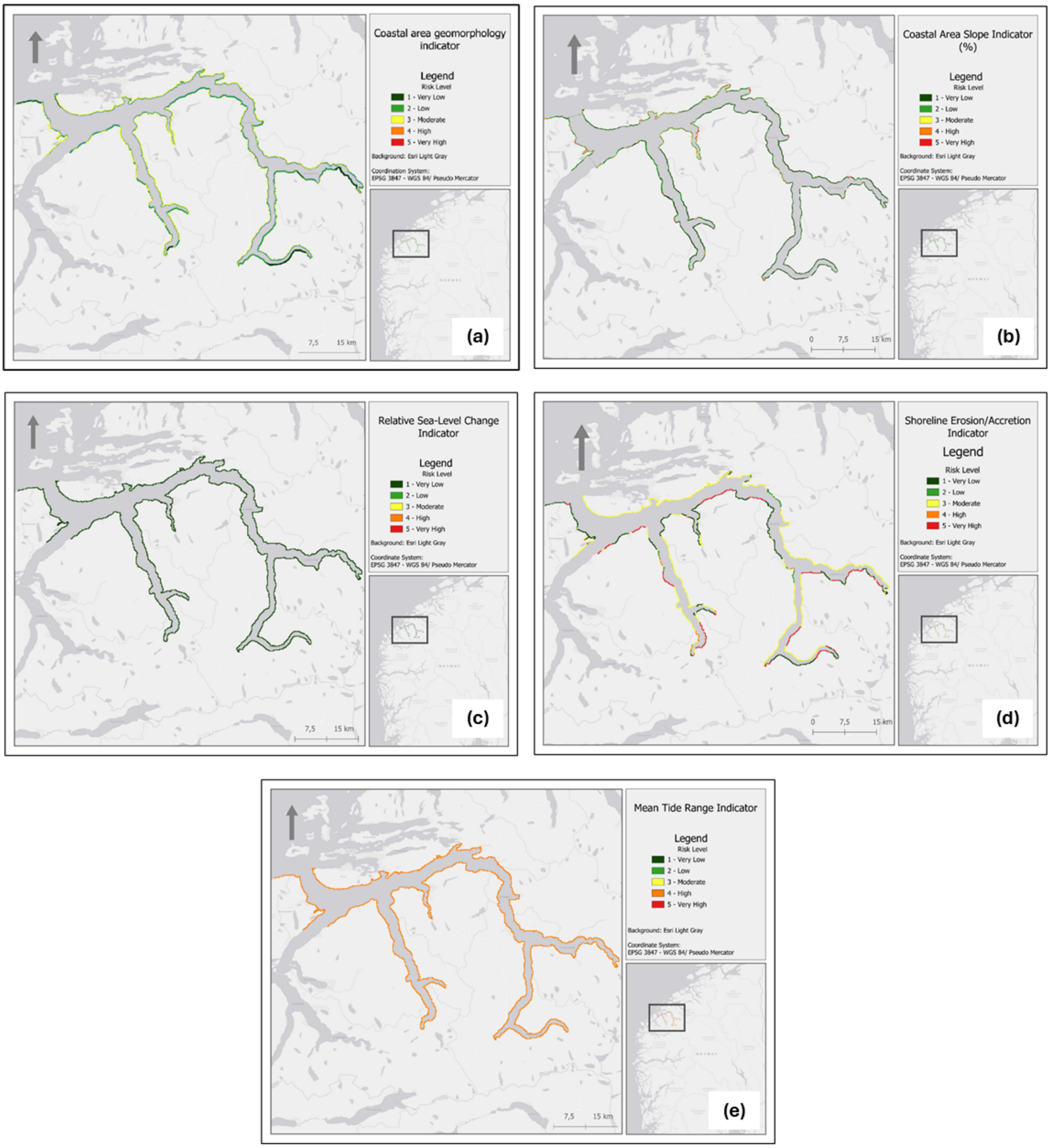

Figure 4. *Maps depicting the vulnerability assessment of individual CVI (Coastal Vulnerability Index) factors:(a) Geomorphology ranking, (b) Coastal slope ranking, (c) Relative Sea level change ranking, (d) Shoreline erosion/accretion ranking, and(e) Mean tide range ranking. Red hues represent Very high and high degrees of vulnerability, yellow moderate degree of vulnerability and green hues Low and very low degree of vulnerability*

5. Discussion

The objective of this study was to assess the vulnerability of a fjord system in Norway using the Coastal Vulnerability Index (CVI) in conjunction with geospatial datasets. The results indicate that the degree of coastal vulnerability in the studied area ranges from low to moderate. The analysis highlights that the most critical factors affecting CVI are relative sea level change and mean tide range, both contributing to very high vulnerability along the entire coastline. Following these, coastal slope and shoreline erosion/accretion are also significant, with high vulnerability observed in most parts of the coastline.

Mean wave height plays a moderate role, as evident in vulnerability patterns across the area. The factor with the least influence is geomorphology, which indicates low vulnerability throughout the coastline, consistent with findings from similar studies in similar experimental set-ups such as Finland and other parts of Norway that attribute low vulnerability to the geological composition of the coastlines (Kovaleva et al., 2022; Toumasi et al., 2024).

Results align with findings from other Arctic studies, such as those on Longyearbyen, Svalbard (Jaskólski et al., 2017), where high vulnerability correlates with low coastal slope and limited sediment supply, particularly in deltaic systems. Similarly, human interventions, such as the construction of artificial coastlines, significantly influence CVI values, as observed in Longyearelva Delta. Comparative studies from other regions, such as the Eastern Gulf of Finland and the Croatian coast of Istria, reveal moderate to low coastal vulnerability (Kovaleva et al., 2022; Šimac et al., 2023). These findings underscore the importance of regional geomorphological and climatic factors in determining coastal vulnerability. Compared to the literature and sources with a similar focus, such as the studies by (Creel et al., 2022; Hansen et al., 2007), the similarities that emerge are the alteration of the anaglyph and the variations in the values of variables such as mean wave height.

A notable methodological limitation of this study arose from assigning equal weight to all factors in the CVI calculation. This uniform weighting does not reflect real-world dynamics where certain factors, such as relative sea level change and shoreline erosion, may have greater impacts. Future studies should incorporate differential weighting to enhance accuracy. Furthermore, this research lays the groundwork for integrating socio-economic indicators alongside physical geography to provide a more comprehensive vulnerability assessment. The EO-PERSIST project, emphasizing socio-economic studies in Arctic environments, offers a promising resource for addressing data gaps and developing methodological approaches to integrate socioeconomic with geospatial datasets to assess coastal vulnerability (Petropoulos et al., 2023). By addressing these challenges and leveraging robust databases, like the one that EO-PERSIST aims to develop, future studies can refine CVI methodologies, ensuring accurate assessments and informing sustainable management practices for vulnerable Arctic coastlines.

Final Remarks

The aim of the study was to assess the coastal vulnerability of the fjords in the study area using geoinformatics. By observing the results produced and analysing the individual elements and their combination, it is possible to compare them with the initial hypotheses set. Geomorphology, coastline and coastal vulnerability index contribute to this, creating the differences. As far as geomorphology is concerned, it has a positive sign in its influence on the area, due to the low risk along the entire length of the area. Similarly, the coastline is characterised for the most part by low risk, with the exception of certain parts where it is moderate or increased, which are worthy of observation. Finally, the coastal vulnerability index shows mixed results, with the predominant ones being moderate and low risk. In terms of the problems encountered, the first is the reduced list of satellite imagery near the poles, specifically in the earlier time periods. The second is the little information on the waters, which may be due to the limited number of tide gauges in the area.

Following the progress and development of the work, a future direction is to combine this information with the anthropogeographic data, so that the work has a practical application. A continuation of this is more targeted research as a reference to the distribution of this population within the urban fabric, which areas need more attention depending on the size of the population and the type of problem that plagues each area. At the same time, one issue that can be taken into account is human intervention in the area and how it has shaped the landscape over the years. Finally, an equally important addition to the above is research into how glaciers affect the coastline and submarine relief during the winter period. By combining all of the above suggestions with the results of this work, a comprehensive CVI model can be created. This, can be applied to any region regardless of the prevailing geographical and political conditions, making it suitable for any region of the world. Still, a more targeted analysis of the current study area would be to calculate the future shape of the study area's relief, with the aim of preventing disasters and taking advantage of opportunities that may arise.

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