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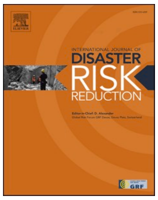

Hazards and resilience of subsea telecommunications connections for small islands

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ABSTRACT

Small islands are among the most telecommunications-dependent communities on Earth, yet often the least resilient to network disruption, despite their importance for communications, education, healthcare and economic activity. However, global assessments of subsea cable vulnerability have largely overlooked the specific hazards and structural constraints affecting small islands. Here, we assess telecommunications resilience for small islands by integrating a 40-year global database of 5113 subsea cable faults with spatial analyses of environmental and anthropogenic hazard exposure. We analyse 24 island and island groups worldwide, representing diverse geological, economic, and oceanographic settings, and evaluate hazard exposure related to their offshore environments.

We find that island-proximal environments are disproportionately hazardous for subsea cables, with over 75% of faults on island-connecting systems occurring within 300 km of island coastlines. Globally, 71.4% of faults are attributed to anthropogenic causes, and logistic regression shows that increased anthropogenic exposure significantly raises the likelihood of fault occurrence (odds ratio = 2.22, $p = 0.006$). In contrast, no significant relationship is observed between natural hazard exposure and fault occurrence ($p > 0.4$), suggesting that route design and engineering mitigation effectively reduce impacts from routine natural processes. However, extreme natural events can still cause widespread, multi-cable system failures.

Small Island Developing States (SIDS) are particularly vulnerable, with fewer international cable connections (mean 3.9 vs 6.9 for non-SIDS) and greater distances from repair hubs (~2200 km vs ~1800 km), increasing both the likelihood and duration of outages.

These findings demonstrate that cable vulnerability is spatially concentrated and hazard-type dependent, requiring region-specific resilience strategies. Strengthening telecommunications

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resilience for small islands will require not only improved engineering and hazard assessment, but also increased network redundancy, regional cooperation, and targeted investment.

1. Introduction

1.1. Why telecommunication resilience matters for small islands

Subsea telecommunications cables carry more than 99% of all digital data worldwide, underpinning the internet, enabling the rapid and reliable transmission of data between continents and supporting everything from international trade to everyday communication. There are 1.8 million kilometres of in-service cable currently on the seafloor (Fig. 1), connecting business and communities around the planet [1]. Islands are by their definition isolated, separated from other landmasses and communities by bodies of water. Small islands or island groups are often particularly reliant on telecommunications. Where local populations are too small or dispersed to support centralised services, telecommunications provide a critical remote connection not just to family and friends, but also to essential services, like medicine and education. Telecommunications also support the international transfer of funds, essential for business services, and reliable telecommunications support business growth. For example, a planned new international Fijian cable is calculated to contribute USD295 million GDP between 2024 and 2030, creating 3600 jobs in 2030 alone [2]. For many small islands, telecommunications also support the payment of remittances (payments sent home from family or friends working abroad), which may form a substantial proportion of GDP [3].

While recent media coverage has tended to focus on the threat posed to telecommunications from hostile attacks on the subsea cable network that supports it, such instances of intentional damage account for less than 0.1% of instances of cable damage [6–8]. Instead, it is unintentional damage or events that account for almost all subsea cable faults, with several recent high-profile telecommunications outages highlighting the vulnerability of island networks to outages as a result of both accidental human activities and natural causes. For example, the eruption of Hunga Volcano in 2022 disconnected islands in the Kingdom of Tonga from the global internet for between 5 weeks and 18 months [9], while the loss of broadband and mobile connections on Shetland for over a week in 2022 was the result of accidental damage to a subsea cable by fishing gear [10]. Unlike hostile actions, these hazards have existed since the first cables were laid and thus, we have a record of their impacts on telecommunications cable networks over past decades (Carter et al., 2014). Such hazards are also often spatially restricted, due to controls on the conditions that generate them, e.g. fish stock concentrations, ocean currents, seafloor morphology, and for some events, e.g. storms, they may be forecastable on both short and long timescales [11,12]. Thus, these types of hazards are not only vastly more common than sabotage, they are in many cases also more

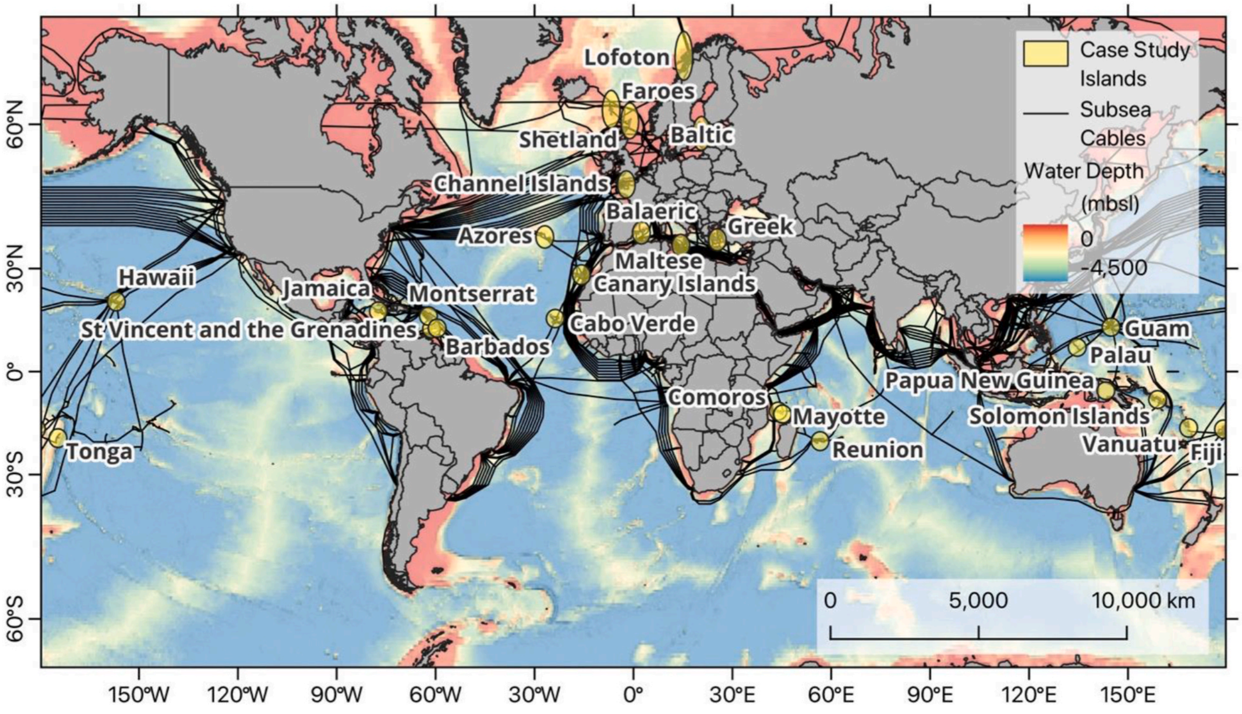


Fig. 1. Global map showing the approximate locations of global subsea telecommunications cables (taken from TeleGeography [4] overlying a map of seafloor depth [5]. The locations of the islands and island groups used in this study are highlighted by the yellow circles (300 km buffers around the central point of the island or island group).

forecastable, and thus possible to mitigate against.

This global study focuses on small islands as a distinct class of infrastructure systems, encompassing a wide range of geological settings, economic contexts, and hazard regimes. Across these environments, small islands face a combination of high dependence on telecommunications, limited redundancy in network connections, geographic isolation from repair capacity, and concentrated exposure to hazards in nearshore zones. These hazards include both natural processes, such as volcanic eruptions, storms, and submarine mass sediment flows, and anthropogenic activities, such as fishing and anchoring, which together shape patterns of cable damage observed worldwide. While previous studies have examined global cable fault datasets or individual hazard processes [12–15], no study has systematically assessed how hazard exposure, historical faults, and network structure interact specifically in small island settings at a global scale.

For small islands, natural and accidental anthropogenic damage to telecommunications infrastructure is a particular concern [1,16,17]. Some islands are connected by only a single subsea cable, or rely on fragile land-based infrastructure, and thus have multiple single points of failure that are vulnerable to such hazards [17–20]. Small islands often also face multiple combined hazards, increasing this risk. For example, many islands are volcanoes or built by volcanic activity, resulting in a combination of volcanic hazards relating to eruptions, alongside highly rough, hard seafloors, complicated near seabed currents, and a risk of submarine landslides. Many islands are also facing the impacts of increasing tropical storm frequency and intensity, compounded by sea-level rise as a result of anthropogenic climate change [19,21]. Thus, small islands combine a high exposure to hazards, with highly vulnerable infrastructure.

1.2. *Defining "small islands"*

Both the term "small islands" and the associated "Small Island Developing States (SIDS)" or "Large Ocean States (LOS)" are relatively loosely defined in terms of metrics. SIDS/LOS are not defined based on size or population but are instead are a group of UN Member States and Non-UN Members/Associate Members of United Nations regional commissions that face unique and common social, economic and environmental vulnerabilities [22]. SIDS/LOS are located in the Caribbean, Pacific, Atlantic, Indian Ocean and South China Sea. Small islands may be located anywhere and are variably defined in different studies, for example as land masses surrounded by water that have an area of $<10{,}000$ km^2 and a population of $<500{,}000$ [23], or more loosely as "*Those specks of land [surrounded by water] large enough to* support *permanent residents, but small enough to render to their inhabitants the permanent consciousness of being on an island.*" [24]. Small islands fall into different categories: (i) independent island states (which may include Small Island Developing States); (ii) islands that are an autonomous region of a mainland state (such as the Portuguese Azores); and (iii) islands that fall under the rule of a mainland state (such as Scottish Islands like Orkney) [25]. When looking at resilience, it is perhaps most useful to follow the UN style of classification, by including all islands with similar characteristics that make them vulnerable. In the case of telecommunications, these are islands or groups of islands anywhere on the planet that are reliant on telecommunications to enable education, healthcare or day-to-day business activities, far enough from major land masses that they rely on subsea cables, with small enough populations that they are unlikely to be able to make business cases for large numbers of international connections.

1.3. *Causes of telecommunications outages*

Telecommunications outages can be caused by damage to any of the infrastructure that supports connections, including subsea telecommunications cables that transmit data, landing-stations and beach manholes, and land-based infrastructure that carries and transmits data, as well as other infrastructure that supports this, for example power supplies.

There are around 200 instances of subsea telecommunications cable damage reported every year [8,11]. Given the lengths of cable deployed on the seafloor, and the challenging terrains through which many cables run, this is to be expected (and instances of cable damage per km of deployed active cable have decreased over the last decades). However, this means that subsea cable damage is still a relatively common cause of telecommunications outages. Subsea cables can be damaged in different ways, including chafe and abrasion caused by movement of the cable by natural processes (e.g. seafloor currents) and its interaction with an irregular seafloor, accidental human damage caused by fishing or anchor dragging across cables that lie at or near the seafloor, and natural hazards like submarine landslides, turbidity currents or volcanic eruptions (Carter et al., 2014; [12]). The storminess or general weather conditions in a region may also limit the ability of repair vessels to conduct timely repairs in the event of damage [11]. Cable landing stations and beach manholes may be damaged by coastal inundation as a result of storm surges or sea-level rise, coastal erosion, and by natural hazards, like earthquakes, volcanic eruptions and tropical storms, which may directly or indirectly cause damage (e.g. through pyroclastic density currents generated by volcanic eruptions, or fires following earthquakes) [1,11,12,26–29]. Infrastructure on land includes both the fibre-optic cables and masts that carry and transmit data, as well as all the supporting infrastructure, including power supplies, cooling systems, and the availability of key personnel to access and maintain these services. These systems are vulnerable to a wide range of damage, from natural hazards like storms, earthquakes, volcanic eruptions and flooding, to accidental fires, mechanical failures and social or political unrest. Both offshore and onshore infrastructure may also be deliberately sabotaged, but is rare, and small islands are unlikely to be the target of such attacks; hence, this is not discussed further here. Material faults in cables or infrastructure may also occur as a result of manufacture or installation, but these faults are also rare and therefore are also excluded from later analysis [8].

The location of small islands fundamentally affects their exposure to hazards, their physical and economic resilience, and the vulnerability of the communities impacted [11,12,30]. For example, a small island in north-west Europe is likely to be more economically resilient than a SIDS/LOS due to greater regional interconnectivity but may be more reliant on high-capacity telecommunications connections for high volumes of financial transactions, business activities and digital data traffic. Despite such differences, there are many commonalities that make small islands vulnerable to telecommunications outages, which include their greater reliance on subsea cable supported telecommunications (compared to mainland communities) for business, finance, telemedicine, education and communication, their relatively small number of international and/or mainland cable connections compared to larger islands or nations, their remoteness and exposure to compound hazards, and their exposure to heightened impacts of climate change.

Despite the critical importance of telecommunications for small islands, most previous studies have focused either on global-scale assessments of subsea cable vulnerability or on individual hazard processes (e.g. submarine landslides or storms), with limited attention to how these risks are specific to or compounded by island settings. Small islands represent a distinct class of infrastructure vulnerability, characterised by strong dependence on a small number of cable connections, geographic isolation from repair capacity, and exposure to both concentrated human activity and localised natural hazards. However, there has been no systematic global assessment of how hazard exposure, historical cable faults, and network structure interact to influence telecommunications resilience for small islands. Addressing this gap is essential to inform targeted resilience strategies for these essential but structurally vulnerable systems.

Here, we show that the environments surrounding small islands are disproportionately hazardous for subsea telecommunications cables, with the majority of faults occurring within near-island regions. We further demonstrate that anthropogenic hazards are more strongly associated with observed cable faults than natural hazards, while structural factors such as limited connectivity and remoteness from repair capacity amplify vulnerability, particularly for Small Island Developing States. To address these issues, we combine historical cable fault data with spatial analyses of hazard exposure across multiple island settings, first examining patterns of cable faults, then assessing variability in hazard exposure, and finally evaluating relationships between exposure, fault occurrence, and implications for resilience.

1.4. *Aims of this study*

In this study, we provide the first global assessment of subsea telecommunications resilience for small islands. We integrate a 40-year database of subsea cable faults with spatial analyses of environmental and anthropogenic hazard exposure across 24 island and island groups representing a range of geological settings, economic contexts, and hazard regimes. Rather than focusing on individual islands, this work adopts a comparative global approach to assess small islands as a distinct class of infrastructure systems.

Specifically, we (i) quantify the spatial distribution and causes of historical cable faults in island-proximal environments, (ii) assess variability in exposure to key hazard types across different island settings, (iii) evaluate the relationship between hazard exposure and observed fault occurrence, and (iv) examine how network structure and logistical constraints influence overall resilience. Through this combined approach, we identify the key drivers of vulnerability and provide a basis for region- and context-specific strategies to improve telecommunications resilience for small islands globally.

2. Methods

This study follows a multi-step analytical workflow combining historical cable fault data with spatial analyses of hazard exposure and network characteristics. First, a global database of subsea cable faults is compiled and filtered to isolate faults associated with island-connected systems. Second, a set of environmental and anthropogenic hazard variables is extracted from global datasets and analysed within standardised 300 km buffer zones around each island or island group. Third, relationships between hazard exposure and observed fault occurrence are evaluated using statistical analyses. Finally, network characteristics, including connectivity and distance to repair capacity, are assessed to examine their influence on overall resilience.

2.1. *Cable faults database*

We first analyse the global cable fault database - a 40-year industry database compiled and provided by OceanIQ that documents past instances of cable faults on the global network, with the records we analyse continuing until 2019. Fault attributions were assigned by the repair company where one could be confidently discerned. In cases where no cause is apparent, they were assigned an unknown attribution. Attribution categories in the database are: Anchor, Branching Unit, Cable, Cable Crossing, Corrosion, Dredging, Fishing-Trawling, Ice, Joint, Landslide, Other 3rd Party, Chafe, Maintenance, Nature, System, Repeater, Seismic and Suspension. To simplify analysis we remove all faults associated with manufacture or installation (categories: Branching Unit, Cable, Cable Crossing, Corrosion, Maintenance, System and Repeater), we group Nature, Landslide, Seismic and Ice hazards into a single Natural Causes category, and group Suspension and Chafe into a single category. Thus, we examine 5113 global faults across the following categories: Anchor, Dredging, Fishing, Other 3rd Party, Natural Causes, Chafe and Suspension, and Unknown. Global regions were assigned using the Marine Regions Global Oceans and Seas shapefiles (Flanders Marine Institute[31]). All data were projected in QGIS version 3.40.3-Bratislava and faults were initially separated into regions based on their regional ocean region (Arctic, Baltic, Indian, Mediterranean, North Atlantic, South Atlantic, North Pacific, South Pacific, South China and Southern).

We then selected 24 individual islands and island groups (Fig. 1; St Vincent and the Grenadines, Montserrat, Barbados, Jamaica, Comoros, Mayotte, Kingdom of Tonga, Fiji, Palau, Guam, Solomon Islands, Vanuatu, Papua New Guinea, Hawaii, the Azores, the Canary Islands, Faroe Islands, Shetland, Channel Islands, Baltic Islands, Lofoten Islands, Balearic Islands, Maltese Islands and Greek Islands). The selected islands and island groups were chosen to provide a representative cross-section of small island systems globally, encompassing a range of physiographic and socioeconomic conditions. This includes both volcanic and non-volcanic islands, which differ in their exposure to geohazards such as earthquakes, volcanic activity, and submarine mass movements, as well as in seafloor morphology and nearshore processes. The dataset also spans multiple ocean regions (e.g. Pacific, Atlantic, Mediterranean, and Indian Oceans), capturing variability in storm regimes, oceanographic conditions, and levels of marine activity.

In addition, the selection includes both Small Island Developing States (SIDS) and non-SIDS, allowing comparison between systems

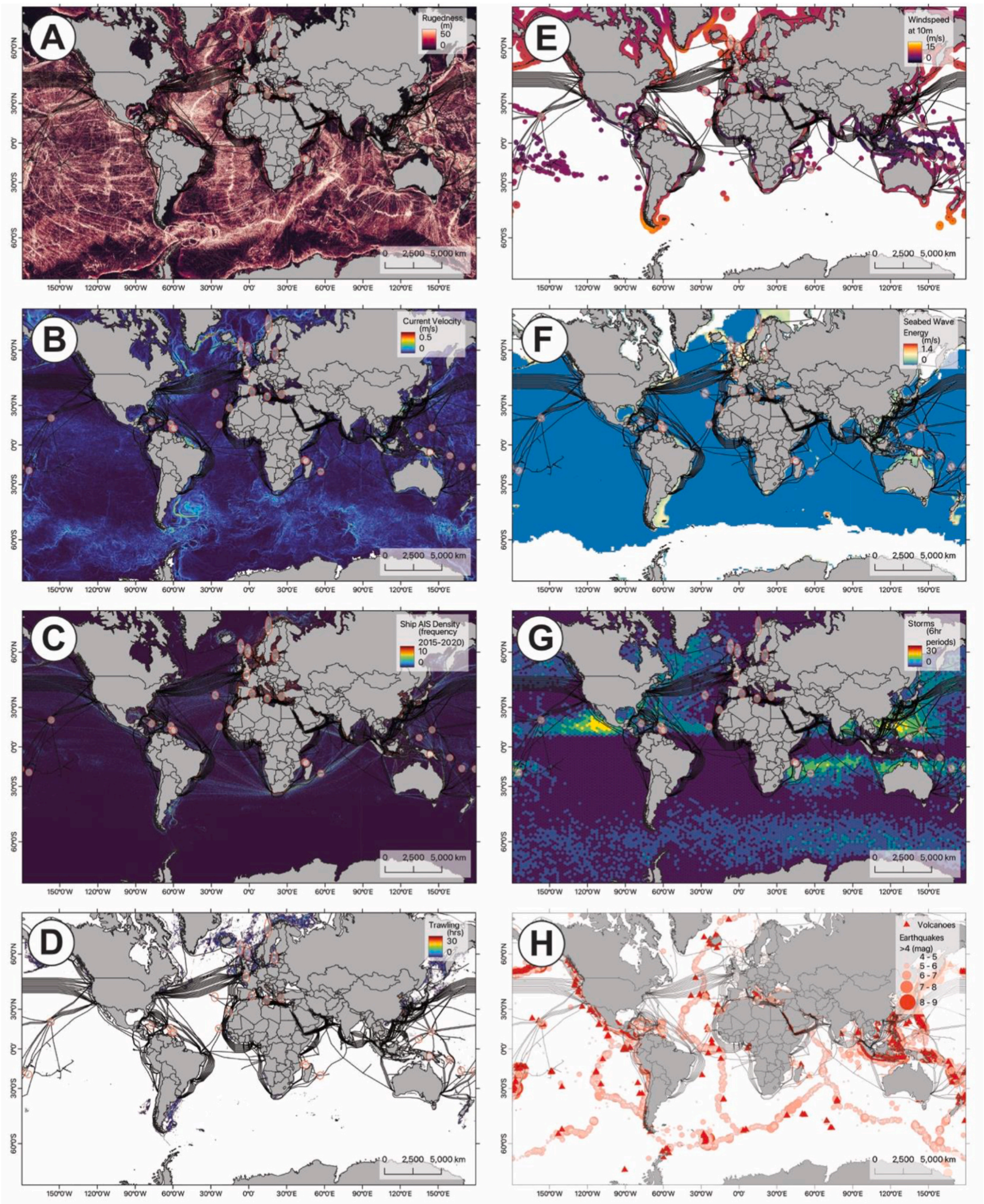


Fig. 2. Global datasets analysed for cable fault exposure. (A) Terrain Ruggedness Index derived from GMRT database [44]; (B) Seabed current velocity extracted from the GLORYS12V1 product is the CMEMS global ocean eddy-resolving (1/12° horizontal resolution, 50 vertical levels) reanalysis covering the altimetry (1993 onward); (C) Global ship traffic extracted from AIS information [37]; (D) Global bottom trawling data [38]; (E) Windspeed at 10 m above sea/ground level [39]; (F) Seabed wave energy extracted from the spectral wave model WaveWatch III; (G) Storm density (for display binned into 250 × 250 km hexagons), count is the number of 6 h periods the storm track spend in each cell, data extracted from International Best Track Archive for Climate Stewardship (IBTrACS) for the period 2006 – 2016 [40] and from the NASA database of extra-tropical storms for the same period [41]; (H) Earthquakes occurring with a magnitude over 4 between 2020 and 2025 [42] and volcanoes with Holocene activity recorded in the Smithsonian Database [43].

with differing levels of economic capacity, infrastructure redundancy, and connectivity to the global telecommunications network. The islands vary in the number of cable connections, degree of geographic isolation from repair capacity, and intensity of anthropogenic activity (e.g. shipping and fishing), enabling assessment of how both environmental and socioeconomic factors influence telecommunications resilience. The aim was not to provide exhaustive coverage of all island systems, but to capture the range of conditions under which subsea telecommunications operate.

A 300 km buffer was chosen as a pragmatic spatial scale to capture the dominant processes influencing cable vulnerability in island-proximal environments. This distance is sufficient to encompass the majority of nearshore anthropogenic activities, such as fishing and anchoring, which are concentrated on continental shelves and slopes, as well as geomorphic and oceanographic processes including submarine landslides, turbidity currents, and strong seabed currents, which can extend tens to hundreds of kilometres from source regions (e.g., Carter et al., 2014; [9,32]). At the same time, the buffer is constrained to minimise inclusion of open-ocean processes that are less directly influenced by island settings. Further justification of the 300 km buffer is provided in Appendix 1.

The cable faults database was also used to assess whether or not local areas adjacent to islands are more hazardous for subsea cables than the ocean regions in which they are found. In order to do this, we isolated all the faults associated with cables that connect to the case study islands by isolating these cables and buffering them by 20 km (to account for inaccuracies in positioning, movement on the seafloor, or recording inconsistencies in position for cable repairs at the repair site) then extracting all the faults within these buffers from the faults database (using the "select by location" function in QGIS). For the cable faults for each island group, we then calculated how many faults lie within 300 km of that island group (based on the buffer circle), how many lie within 300 km of another island (done manually by cross referencing a 300 km buffer from the coastline shapefile), and how many lie within 300 km of mainland coastlines. We also extracted the total lengths of cable supplying islands and island groups, the number of systems involved in connecting them, and water depths of the faults from the GIS.

2.2. Hazard exposure analysis

To compare the documented historical cable faults with our assessment of exposure to potentially hazardous conditions we then quantify hazard exposure. We used the 300 km island group buffers within which to analyse the exposure to different hazards in the immediate vicinity (Fig. 2). We assessed the following variables.

A. Seafloor ruggedness (Fig. 2A): Terrain Ruggedness Index (TRI), defined as the mean difference between a central pixel and its surrounding cells, was derived from the General Bathymetric Chart of the Oceans (GEBCO) at 450 m resolution using QGIS Raster Analysis. Terrain Ruggedness Index (TRI) was selected as a simple and widely used [33–35] metric of seabed heterogeneity that is computationally efficient and suitable for global-scale analysis. While alternative metrics such as Vector Ruggedness Measure (VRM) or Topographic Position Index (TPI) may capture additional aspects of terrain complexity, TRI provides a robust and consistent proxy for seabed roughness across diverse environments at the spatial resolution considered here. The mean value within the 300 km buffer zone was compared between island groups.
B. Current velocity at seabed (Fig. 2B): Currents are taken from the GLORYS12V1 product is the CMEMS (Copernicus Marine Environment Monitoring Service) global ocean eddy-resolving (1/12° horizontal resolution, 50 vertical levels) reanalysis covering the altimetry (1993 onward). The model component is the Nucleus for European Modelling of the Ocean (NEMO) platform driven at surface by ERA data [36]. Daily mean currents are extracted for the lowest active model grid box of the 50 standard levels. The mean seafloor current speed within the 300 km buffer zone was compared between island groups.
C. Marine Traffic (Fig. 2C): Global data for marine traffic was used as an indicator of the commercial usage of the area and the potential risk of anchor drags or other accidental damage. Data were produced with IMF, as part of IMF's World Seaborne Trade Monitoring System [37] and downloaded from the World Bank. This dataset is based on all observed ship movement from 2015 to 2020, at 500 m resolution.
D. Bottom Trawling (Fig. 2D): Trawl data were extracted from the publicly available Global Fishing Watch database for a year long period (2016) [38]. Total trawl hours within the 300 km buffer zones were compared between island groups.
E. Windspeed (as a proxy for weather) (Fig. 2E): Mean windspeed at 10 m above ground/sea level was extracted from the publicly available Global Wind Atlas [39] for the period 2008-2017 as an indicator of general marine weather conditions, particularly important for the ability of repair vessels to find weather windows for repairs if required.
F. Wave action at the seabed (Fig. 2F): The global wave model data are produced using a configuration of the spectral wave model WaveWatch III. The global configuration consists of a Spherical Multiple Cell grid with a resolution of 0.703° (longitude) x 0.469° (latitude), extending from ~80°N to 80°S. The model is forced by winds and sea-ice. Further described in: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018JC013866. From this model, we extracted the significant wave height (H_s), and mean wave period (T_e) giving a value for wave energy ($E = H_s{*}H_s{*}T_e$). Then, this energy map is combined with the water depth, as exposure = energy/depth. The wave model was forced by ERA-Interim winds and ice for the period 1979 - 2015.
G. Storms (Fig. 2G): Data were extracted for the tracks of tropical storms from International Best Track Archive for Climate Stewardship (IBTrACS) for the period 2006 – 2016 [40] and from the NASA database of extra-tropical storms for the same period [41]. Positions of storms was plotted from both databases for 6-h intervals and this count was used to assess exposure to storms. No weighting was applied for windspeed or storm severity.
H. Geohazards (Fig. 2H): We consider geohazards for which there are consistent global catalogues. The number of earthquakes occurring with a magnitude over 4 (moderate to severe earthquakes likely to be capable of causing seafloor displacement or

shaking that may trigger submarine mass flows) for the period 2020-2025 [42]. The number of volcanoes with an eruption in the Holocene was extracted from the Smithsonian Global Volcanism Program Catalogue [43].

Additionally, data on the number of cable connections (and planned future connections) between individual islands and connecting islands and island groups to the global network were extracted from the open access map in Telegeography [4], which allows us to ascertain in-service subsea cable connections that are currently in operation and those that are planned and have been commissioned for installation.

The spatial datasets used in this study vary in both horizontal and vertical resolution, reflecting differences in data sources and modelling approaches. Rather than resampling all datasets to a common grid, which would reduce the information to the lowest resolution, each dataset was retained at its native resolution to preserve the original data fidelity.

To ensure comparability, all variables were analysed within a common spatial framework based on 300 km buffer zones around each island or island group. For each variable, values were aggregated within these buffers (e.g. mean or total, depending on the dataset), thereby reducing sensitivity to differences in spatial resolution. At this scale, the influence of fine-scale spatial variability is minimised, and the results represent regional patterns of hazard exposure rather than localised conditions.

Differences in vertical resolution (e.g. modelled seabed currents versus surface wind speeds) reflect the specific physical processes represented or the best available model output and were therefore retained as provided. Each variable is used as an independent proxy for a distinct hazard mechanism, and variables are not directly compared on a point-by-point basis. This approach allows consistent comparison across datasets of differing resolution while preserving the physical meaning of each variable and maintaining a focus on regional-scale patterns relevant to subsea cable vulnerability.

This study uses a combination of observational datasets and model-derived variables to assess relative patterns of hazard exposure. As such, several sources of uncertainty should be considered. These include differences in spatial resolution between datasets, the use of proxy variables to represent complex physical processes, and the aggregation of data within large spatial buffers. In addition, model-derived datasets (e.g. ocean reanalysis and wave models) contain inherent uncertainties associated with their input data and parameterisations. Consequently, results should be interpreted as regional-scale indicators of relative exposure and vulnerability, rather than precise or site-specific predictions.

2.3. *Correlation of hazard exposure with documented cable damage*

Next, we assess relationships between exposure and faults. Both the exposure analysis and the historical observed cable fault data can be grouped into three categories: anthropogenic (fishing, anchor drags (shipping intensity serves as a proxy) or other 3rd party damage); chafe and abrasion (as a function of rough seafloor and high seabed currents); and natural hazards (earthquakes, volcanoes, storms). In regions where exposure to one of these categories is higher, one might expect an increase in the faults caused by that category, e.g. in an area of intense trawling one would expect more fishing related faults. To test if this is the case, we analysed relationships between cable exposure metrics and observed cable fault data across these three categories. For each category, we considered two variables: i) Hazard exposure (a continuous percentage metric extracted from the normalised data plotted in Figs. 2 and 3); and ii) Faults (a percentage representing the proportion of faults attributed to that category, excluding those that were unknown and regions where no faults have occurred in the buffer zone). Papua New Guinea was also excluded as its buffer zone is smaller than the islands. Because several of the faults variables were heavily zero-inflated (many observations with no recorded faults), we created binary indicators of fault presence (Binary = 1 if the observed value was >0, otherwise 0). This approach enables both correlation-based analysis of continuous variables and regression-based tests of whether exposure levels predicted the occurrence of faults.

Normality of continuous variables was assessed with the Shapiro–Wilk test [45] for each grouping of data n = 20. Given that fault

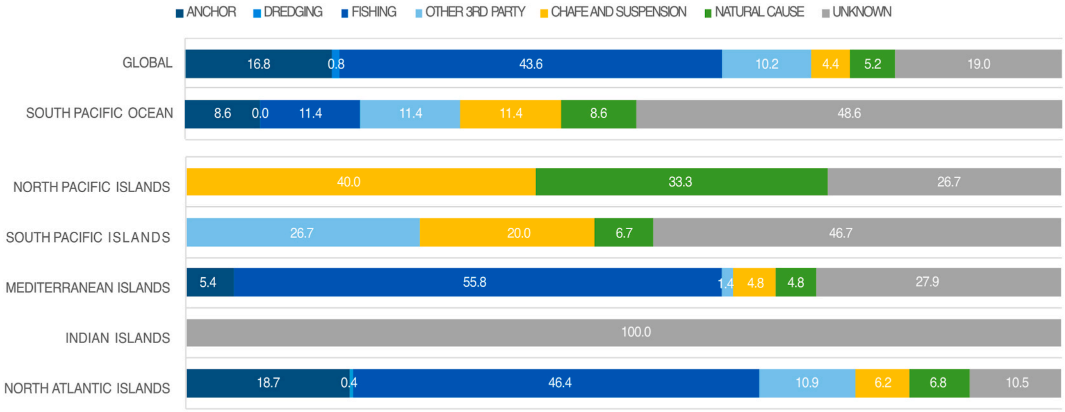


Fig. 3. Percentage of total cable faults attributed to different factors (based on the Global Marine Cable Faults Database from 1960 to 2019) for the global region and the South Pacific Ocean region, and for buffer zones 300 km around case study small islands or island groups grouped by their ocean region.

distributions were frequently non-normal and skewed, we used Spearman's rank correlation coefficient (ρ) and Kendall's tau (τ) to examine associations between exposure and faults within each category. To investigate whether exposure predicted the presence of faults, we modelled each binary fault variable (Anthropogenic, Chafe and Abrasion, Natural) as a function of the corresponding exposure variable using binary logistic regression. Likelihood ratio tests were used to evaluate overall model fit, and odds ratios were calculated to quantify effect sizes. We compared exposure levels between regions with and without observed faults using the Wilcoxon rank-sum test (Mann–Whitney U). To aid interpretation, we produced boxplots with overlaid jittered data points for each category.

2.4. *Locations of telecommunications infrastructure and repair vessels*

Finally, for interpretation of the results, locations of submarine cables, numbers of connections and other data were extracted from the publicly available Telegeography Subsea Cable Map [4]. Precise charted locations for cables cannot be presented here but were used for statistical analysis. Locations of home ports for cable repair vessels (to ascertain the remoteness of islands from a cable repair vessel) were identified based on a database from the International Cable Protection Committee [46]. Eight other known cable repair ships not included in this database were also included and related to our best understanding of their home port. Our data points show a good match with identified cable repair ship mobilisation ports by Palmer-Felgate [8].

3. Results

3.1. *Factors that caused cable damage are distinct for small islands compared to broader regional patterns*

Cable fault databases provide insights into the overall causes of cable faults and regional variability, aid in identifying hotspots for cable damage, and record temporal changes in fault causes. Fault causes are broken down into those caused by accidental human activities including anchor drags, dredging activities and fishing, as well as a category for other accidental anthropogenic damage, those caused by natural hazards, like landslides, turbidity currents and volcanic eruptions, those caused by chafe or suspension of the cable, and those for which a cause cannot be assigned. In order to assess variability on a regional basis, we compare regional extracts of the database against the entire global dataset (Fig. 3). Globally, 71.4% of cable faults are caused by human activities, including 16.8% by anchor drags, 0.8% by dredging, 43.6% by fishing, and 10.2% by other activities. Chafe and abrasion account for 4.4% of faults, 5.2% are attributed to natural hazards, and 19% are unattributed.

Faults occurring within the 300 km island buffers are frequently different to faults within the ocean region in which they lie. For example, in the South Pacific island buffers, there are many fewer faults associated with anthropogenic causes than globally, and in the South Pacific region, with a higher percentage of natural hazard-caused faults (it is also worth noting that this database excludes several natural hazards caused faults in the region that occurred in the last 5 years because it only extends to 2019, which would likely

Table 1
Island connecting cable lengths and number of systems, number of faults occurring on the connecting cables and location of those faults with reference to the locations of buffer zones around islands and mainland coasts.

Island Group	SIDS/ LOS	International/Mainland Connections	Length [km]	Faults within 300 km of this island group	Fault within 300 km of any island	Faults within 300 km of mainland	Total within buffers
Azores	*No*	*2*	3472	92%	8%	0%	100%
Balearic	*No*	*5*	1467	100%	0%	0%	100%
Baltic	*No*	*21*	1604	75%	0%	25%	100%
Canary	*No*	*7*	47209	19%	2%	77%	98%
Channel	*No*	*6*	1402	62%	0%	38%	100%
Faroe	*No*	*2*	1201	58%	0%	0%	58%
Greek	*No*	*13*	13912	51%	28%	21%	100%
Hawaii	*No*	*13*	99093	31%	8%	35%	74%
Lofoten	*No*	*2*	5039	N/A	N/A	N/A	N/A
Mauritius & Reunion	*No*	*3*	15558	19%	5%	67%	91%
Mayotte	*No*	*6*	696	100%	0%	0%	100%
Shetland	*No*	*3*	932	81%	19%	0%	100%
Barbados	*Yes*	*4*	1462	100%	0%	0%	100%
Cabo Verde	*Yes*	*3*	8069	33%	0%	33%	66%
Comoros	*Yes*	*4*	1069	100%	0%	0%	100%
Fiji	*Yes*	*8*	13129	19%	63%	13%	95%
Guam	*Yes*	*15*	55346	23%	28%	44%	95%
Jamaica	*Yes*	*5*	2767	100%	0%	0%	100%
Maltese	*Yes*	*5*	1047	100%	0%	0%	100%
Palau	*Yes*	*1*	3843	0%	100%	0%	100%
Solomon	*Yes*	*1*	5469	0%	0%	100%	100%
St Vincent and the Grenadines	*Yes*	*4*	746	100%	0%	0%	100%
Kingdom of Tonga	*Yes*	*1*	1237	100%	0%	0%	100%
Vanuatu	*Yes*	*1*	1253	N/A	N/A	N/A	N/A

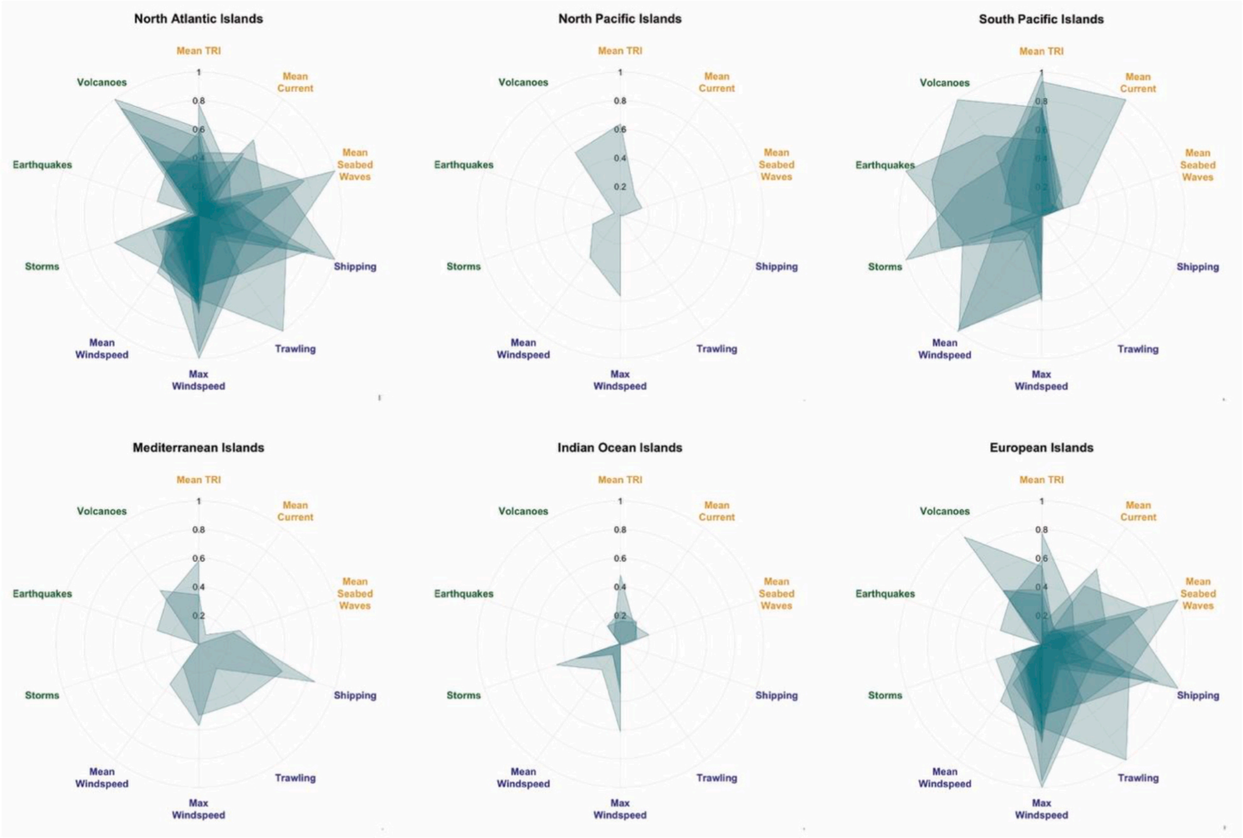
make this trend stronger; e.g. Clare & Yeo et al. [9]) and those due to chafe and abrasion (which are also natural in origin). Similar differences are observed in other regions, suggesting that in many places, small islands have different vulnerabilities to regional trends. The presence of faults with unknown attribution reflects limitations in fault reporting and diagnostic data, particularly in remote regions, rather than the absence of underlying causative processes.

3.2. Island regions are comparatively more hazardous for subsea cables

The difference in faults reveals that conditions (natural and anthropogenic) surrounding islands are distinct to those affecting the ocean regions in which they lie, thus it is important to understand if the areas surrounding islands themselves present an unusually hazardous environment for the cables that connect them. We determined the total length of cables connecting to each island, which ranged from 696 km (Mayotte) to 100,093 km (Hawaii) - with between 0 and 80 faults per 1000 km. For almost every island group studied on which faults had occurred on their connecting cables, the majority of faults occurred close to the island (>75% of faults at 11 of 22 islands or island groups and >50% of faults at 3 further islands or island groups) (Table 1). For those where a large majority of faults were not within 300 km of the connected island, 2 had >75% of their faults within 300 km of another island or island group) and 3 had >75 % of their faults within 300 km of the mainland coast. The only islands or island groups studied where a substantial number of cable faults occurred outside of these buffers were Cape Verde (33.6%), the Faroes Islands (42%) and Hawaii (26.4%). These islands are connected by relatively long lengths of cable, but other islands with equivalent or longer cable lengths do not show the same pattern. This indicates that in most cases, the most hazardous environments for subsea telecommunications cables connecting small island or island groups, are close to the islands themselves.

3.3. Diverse hazard exposure around small islands

Locations around islands can be particularly hazardous for cables (Table 1), yet display a range of fault attributions (Fig. 3), which indicates a diversity in range of hazard types and geographically variable exposure to those hazards across different regions and island types. In order to examine this further, we investigated the exposure of different islands to a range of factors that cause cable faults


North Atlantic Islands

North Pacific Islands

South Pacific Islands

Mediterranean Islands

Indian Ocean Islands

European Islands

Fig. 4. Radar diagrams showing exposure to different hazardous phenomena within 300 km of the islands or island groups studied, plotted by region. The European subset is also shown without the rest of the North Atlantic due to the high number of European islands included. Hazard exposures are normalised to the maximum value in the dataset to be between 0 and 1, with 1 representing the most hazardous value measured at any island and 0 representing no exposure to that hazard.

including: rough seafloors, high seabed currents, high wave energy, dense shipping (as a proxy for anchor related faults), maximum and mean windspeeds, storms, earthquakes and volcanoes. These were normalised to the maximum recorded value in the dataset to be a value between 0 and 1 and plotted on radar diagrams by region (Fig. 4). This analysis reveals clear differences in the exposure to different hazards between regions, with North Atlantic islands showing the highest diversity, being particularly exposed to hazards relating to human activities. Islands in the South Pacific show a comparatively low exposure to human activities and a higher exposure to natural hazards. Islands in the North Pacific and Indian Ocean are relatively less hazardous than the other island groups, while Mediterranean islands appear moderately less hazardous except for a high relative exposure to shipping. European islands show a similar pattern to the overall North Atlantic, but with less exposure to storms.

In terms of geological origin, the islands in this analysis fall within two broad classes of island: volcanic and non-volcanic. Islands were classified as volcanic or non-volcanic based on their dominant geological origin or that of their immediate surroundings (e.g. volcanic arc, hotspot, or tectonic uplift systems versus continental or carbonate platform systems). In total, 16 islands or island groups (Azores, Canary Islands, Cabo Verde, Comoros, Fiji, The Faroe Islands, Guam, Greek, Hawaii, Mauritius & Reunion, Mayotte, Palau, Solomon, St Vincent and the Grenadines, Kingdom of Tonga, Vanuatu) were classified as volcanic and 8 (Balearic, Baltic, Barbados, Channel Islands, Jamaica, Lofoten, Maltese, Shetland) as non-volcanic. When compared against this classification, the radar plots clearly show a distinction between the primary hazard exposure between these different island types (Fig. 5). Volcanic islands have a much higher exposure to natural hazards, including (unsurprisingly) volcanic hazards, but also rough seafloors, earthquakes and storms. Non-volcanic islands have a much higher exposure to human hazards, including shipping and trawling, as well as high seabed wave energy, likely as a result of their coastlines shelving less steeply than volcanic islands and thus having larger areas of shallow seafloor within the storm wave base.

3.4. How does the assessment of exposure compare to documented instances of cable damage?

While one might expect higher hazard exposure to equate to a higher number of observed cable faults attributed to the same exposure category, we find that this relationship is not statistically robust. Correlation analyses showed no significant associations between exposure and the proportion of faults within any category. For anthropogenic factors, Spearman's ρ was 0.16 ($p = 0.49$) (where the correlation strength ρ is scored between -1 and 1 with values over 0.7 being considered strong and the significance, p indicates the significance, with values < 0.05 indicating significance and higher values typically indicating too large a sample size), and Kendall's τ was 0.16 ($p = 0.34$) (where again the correlation τ is scored between -1 and 1 with values over 0.7 being considered strong and higher significance values indicating statistically less significant relationships). For Chafe and Abrasion, ρ was -0.02 ($p = 0.94$) and τ was 0.00 ($p = 1.00$). For natural factors, ρ was 0.08 ($p = 0.75$) and τ was 0.01 ($p = 0.97$). These results indicate that, when considered as continuous percentages, exposure and fault proportions were not significantly correlated within categories.

Logistic regression models, using binary values for fault absence or presence as the outcome, revealed differing patterns across categories. For anthropogenic faults, the model was significant (likelihood ratio test, $p = 0.006$), with higher exposure associated with increased odds of fault occurrence (odds ratio [OR] = 2.22, 95% CI was not estimable as there is no unique best fit). The odds ratio (OR) is a statistical measure of association that compares the odds of an event or exposure occurring, where OR >1 suggests exposure is

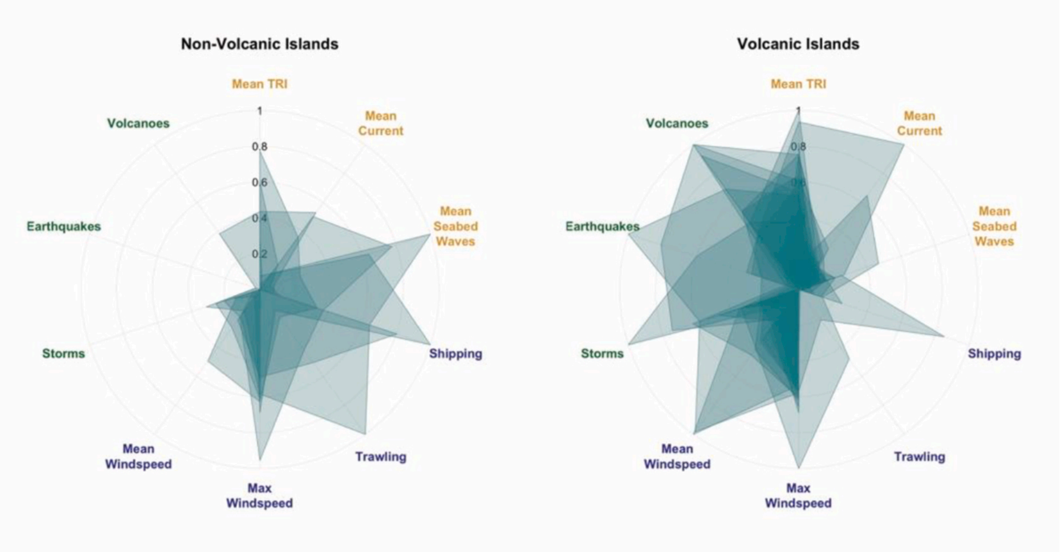


Fig. 5. Radar diagrams showing exposure to different hazardous phenomena within 300 km of the islands or island groups studied, plotted by Island Type (volcanic origin or non-volcanic origin). Hazard exposures are normalised to the maximum value in the dataset to be between 0 and 1, with 1 representing the most hazardous value measured at any island and 0 representing no exposure to that hazard. Where there are groups of islands with different origins, the most common was selected.

associated with higher odds of the outcome. In contrast, chafe and abrasion exposure was not convincingly predictive of fault occurrence (OR = 0.98, p = 0.49), nor was natural exposure (OR = 1.02, p = 0.47). The box plots in Fig. 6 illustrates these patterns. Anthropogenic exposure was consistently higher in regions where faults were observed compared to those without faults. In contrast, distributions of exposure values were largely overlapping for both Chafe and Abrasion and Natural categories, regardless of fault presence. These visual patterns were consistent with the regression results and Wilcoxon rank-sum tests, which showed significant differences only for the Anthropogenic category. Thus, we recognise a statistically valid relationship between anthropogenic exposure and faults that is not present for those caused by chafe and abrasion or by natural causes.

3.5. *Summary of results*

The observed regional differences in fault causes can be directly linked to both physiographic and socioeconomic factors. Regions with extensive continental shelves and high levels of maritime activity (e.g. North Atlantic and Mediterranean) experience elevated exposure to fishing, anchoring, and shipping, resulting in a higher proportion of anthropogenic faults. In contrast, volcanic island systems and many Pacific and Indian Ocean islands are characterised by steeper bathymetry, lower levels of industrial marine activity, and greater exposure to geohazards such as earthquakes, volcanic eruptions, and submarine mass movements. These contrasting environmental and human-use conditions explain the regional variability in both hazard exposure and observed fault attribution.

Overall, three key patterns emerge from the results. First, cable faults are strongly concentrated in island-proximal environments, with the majority occurring within 300 km of coastlines. Second, dominant hazard exposure varies systematically with island type and region, with anthropogenic pressures dominating in high-activity regions and natural hazards more prominent in volcanic and remote island systems. Third, while anthropogenic exposure shows a clear relationship with observed fault occurrence, no equivalent relationship is observed for natural hazards.

4. Discussion

4.1. *Why is there a poor correlation between documented cable faults and exposure to natural hazards?*

The correlation data for hazard exposure and fault attribution should be considered carefully, due to the relatively small sample sizes involved (many regions had experienced only a few cable faults), the limited number of case studies included, the uncertainty in some fault attributions, and the fact that many small islands have only recently been connected, and thus are likely to have experienced fewer faults than those that have existed for decades. However, the lack of any statistical relationship between the factors examined and natural and chafe and abrasion related faults is surprising.

The most likely explanation for this lack of clear correlation is that the cable routes have been well designed by expert cable route engineers, who accounted for the terrain [47], regional natural hazards [48], cable type and weight [49] and which are increasingly using the power of AI to optimise cable routing (e.g. Ref. [50]). Routes are carefully planned based on prior experience and route seafloor surveys, and will be laid to avoid the most hazardous regions. Many natural hazards and seabed inhospitability can be reasonably well assessed from multibeam bathymetric datasets collected before cable installation, and either avoided or mitigated through physical protection (e.g. armouring or burial; Soares and Wang 2025), hence, natural faults and those caused by chafe and abrasion will likely only occur during extreme or unpredicted events in most cases, or where there is no route option that allows such

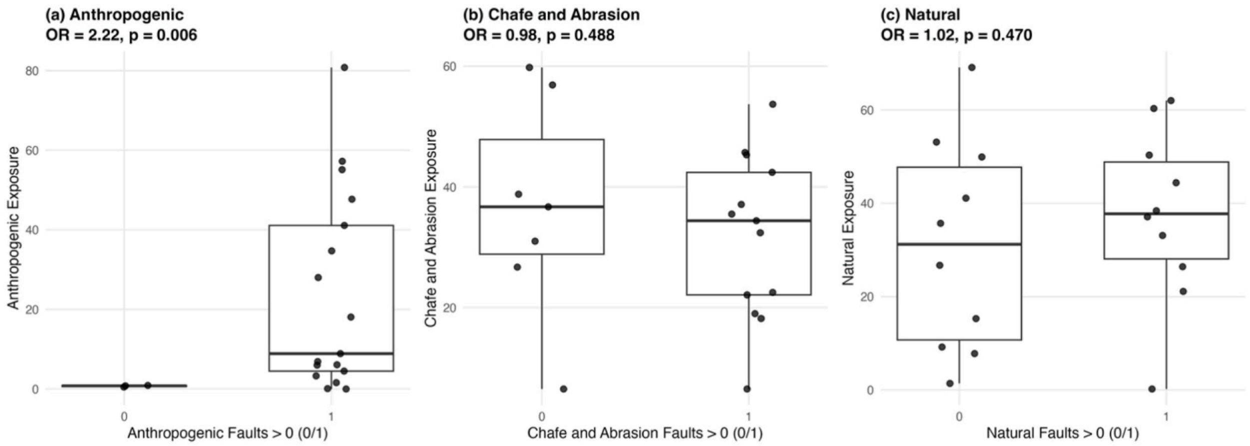


Fig. 6. Box plots with jittered raw data points showing exposure values in regions with and without observed faults across three categories: (a) Anthropogenic, (b) Chafe and Abrasion, and (c) Natural. For each panel, exposure values are compared between locations where no faults were recorded (0) and those with at least one recorded fault (1). Logistic regression results are annotated above each plot as odds ratios (OR) with associated p-values. Higher Anthropogenic exposure was significantly associated with an increased likelihood of cable fault presence (OR = 2.22, p = 0.006), whereas Chafe and Abrasion and Natural exposure showed no significant association.

hazards to be fully avoided. Extreme events tend to have lower recurrence timescales (Carter et al., 2014; [12]), so there may be no signature of previous events obvious in bathymetric data, and/or such events may not have been experienced historically in that region before. Additionally, extreme events may impact much larger regions of the seafloor, and thus a hazard may lie outside the mapped region but be capable of reaching the cable location. For example, long runout sediment density currents can travel for 100-1000s of km and may initiate far from a subsea cable survey corridor [9,51].

While cables are often protected from hazards in a variety of ways in shallow water, including through physical cable protection measures that range from additional steel armouring of the cable itself, burial, or (less common) placement of protective structures (e.g. rock placement, concrete mattresses [52]),these protections have downsides (most notably cost, and increasing the cable diameter and weight), which means they will typically be used selectively, based on the route engineer's assessment of the local hazards. As natural hazards and seabed inhospitability can be assessed from multibeam bathymetric datasets collected before cable installation, this allows effective deployment of cable protection measures in most cases. However, in extreme events, conditions could exceed those expected (for example, high sediment loads during submarine landslides and turbidity currents [13,53], or unforeseen impacts of severe weather [14,15]), and overwhelm armour which would otherwise be sufficient.

4.2. *Why is there better correlation between anthropogenic faults and exposure?*

The more convincing correlation for anthropogenic hazards reflects both that in all ocean regions, anthropogenic activities cause the most cable faults, but also that such hazards seem to be both more frequent and harder to protect against or avoid than low impact frequent natural processes. Based on the available data, the prediction of human activities that result in damage may be more complex than for natural processes such as seafloor currents, as this requires consideration of natural patterns like fish stocks, their decline due to overfishing, response to changing ocean conditions, alongside human and economic decisions, which may change based on factors that cannot be readily predicted by existing models. Available data for modelling is often incomplete, and methods and technology change over the lifetime of a cable system (typically 25 years; [52]). Protecting against human hazards is challenging. Fishing gear typically only penetrates the seabed by a few tens of centimetres but may reach deeper [52]. Anchors can penetrate the seabed by several metres, well within the depth of burial for cables [54]. Thus, both fishing and anchoring present a very real hazard for both surface laid and buried submarine cables and typically exert forces that are capable of damaging cables, even when protected. This likely explains the higher correlation for these datasets, as such hazards are hard to predict and hard to protect against.

Protecting submarine cables from fishing activity is challenging because the risk is both pervasive and structurally difficult to eliminate. Fishing, especially bottom-contact gear like trawls and dredges, remains one of the leading causes of cable damage, particularly in shallow waters where cables must coexist with dense human activity [55]. While technical measures such as armouring and burial are used to mitigate this risk, they are unevenly applied due to cost, seabed conditions, and depth constraints, leaving many cables exposed [55]. From a governance perspective, the problem is compounded by fragmented regulation and the “invisibility” of cable infrastructure, which limits awareness, enforcement, and coordination between fisheries, industry, and states [56]. The regulatory framework for cable protection, such as exclusion zones or reporting requirements, is fragmented across jurisdictions and often weakly enforced at sea [56]. Avoiding cables is not only a technical issue but also a behavioural and economic one. Fishing vessels often operate under strong commercial pressure to maximise catch, which can incentivise the use of efficient but high-risk gear (e.g. bottom trawls) in areas that may overlap with cable routes, especially on continental shelves where both cables and fish stocks are concentrated [55]. Even where cable locations are known, compliance is uneven: charts and advisories may not be consistently consulted, and smaller or less-regulated vessels may lack the capacity or incentives to adhere to avoidance guidelines. As offshore activity intensifies, through expanding fishing, shipping, and resource extraction, pressure on cable routes increases, making prevention reliant not only on engineering solutions but also on effective spatial management and cross-sector cooperation [55]. Even with improved monitoring technologies and growing recognition of cables as critical infrastructure, balancing economic use of the seabed with cable protection remains an ongoing and unresolved challenge [57].

4.3. *Cable resilience strategies for small islands will not be universal*

Our analysis reveals that small islands in different regions, and of different types, face different challenges for cable protection (Figs. 1–3). Non-volcanic islands, and those in the Mediterranean and North Atlantic, appear to face the highest risk of cable damage, as they are the most exposed to fishing and marine traffic. While these events are common and hard to protect against, the damage is typically very localised, meaning that repairs are relatively simple. Volcanic islands worldwide, and non-volcanic islands in the South Pacific, are more exposed to natural hazards given their climatic and geological settings [58–60], but for the most part the exposure to such hazards is easier to predict and therefore to protect against, and thus less likely to cause faults. However, the risk posed by extreme events, that may not have previously been experienced historically or whose behaviour is poorly understood is more challenging to assess and hence predict. Such events, which can include powerful underwater landslides and long runout sediment flows, have been shown to damage large lengths of cable and/or multiple cables synchronously, meaning that when they do occur cable repairs can be far more complicated, requiring multiple vessels, and taking longer to remedy, in some cases more than a year [9,51,61].

In this context, resilience strategies for small island cable systems must be tailored to the specific risk profiles and structural constraints of different island types. For islands exposed primarily to anthropogenic risks, such as those in the Mediterranean and North Atlantic, resilience may focus on enhanced spatial planning and protection measures, including cable burial, routing away from high-traffic zones, and improved monitoring and rapid-response repair capacity (e.g. redundant landing points and pre-positioned repair agreements). In contrast, for volcanic and hazard-prone islands, resilience strategies are more likely to emphasise system-level redundancy, such as the development of diverse cable routes, regional interconnection, and, where feasible, hybrid systems incorporating satellite back-up to maintain connectivity during large-scale natural hazard disruption events [62]. More broadly, the inherent constraints of small island systems, limited economies of scale, remoteness, and exposure to both natural and external economic shocks, mean that resilience must also be institutional and economic, not just technical, including regional cooperation, shared infrastructure governance, and investment in adaptive capacity [63]. Such approaches align with wider understanding of small island resilience, where diversification, and flexibility are critical to reducing vulnerability to both environmental hazards and systemic shocks [63]. Finally, emerging work on digital and network resilience in small island contexts highlights the importance of integrating physical infrastructure planning with broader socio-technical systems, including governance, redundancy in digital services, and community-level preparedness, to ensure that connectivity can be maintained or rapidly restored following disruption [64].

4.4. Telecommunications resilience is not solely related to impacts on subsea cables

Subsea telecommunications cables represent one of the major potential points of failure for small island telecommunications networks. However, other factors may also threaten the resilience and continuity of telecommunications networks. The full system includes not just the subsea cable, but also the landing station and the land-based infrastructure, including the physical infrastructure used to transmit the signals, as well as the power systems and personnel needed to keep it running. A failure in any point of this system can cause reductions in network capacity or regional or total telecommunications network outages. This is exemplified by two recent outages caused indirectly by natural hazards which damaged land-based infrastructure. In December 2024, Tropical Cyclone Chido made landfall on Mayotte, with wind speeds up to 215 km/h damaging telecoms masts and power supplies. Internet traffic dropped to zero on the 14th December and progressively increased due to the repair of land-based mobile network stations, with 90% of internet coverage restored within 20 days [65]. Also in 2024, the island of Efate, in Vanuatu, experienced a $7.3M_w$ earthquake. While the only subsea telecommunications cable connecting Vanuatu to the global network was undamaged by this event, a resulting fire significantly damaged the cable landing station, causing an almost total telecommunications outage that took ten days to restore. In other regions, political instability, social unrest, or conflicts, could cause similar disruption to terrestrial networks (e.g. recent examples due to an airstrike in Israel and attempted coup in Haiti; [15,66,67]).

Table 2

Case study islands in this study, their populations, numbers of populated islands, and/or mainland subsea cable connections [4] and their distance from the nearest hub for a repair vessel. Those classified as SIDS/LOS are separated and the last column shows the mean number of connections and the mean distance from a repair hub for islands/island groups that are and are not SIDS/LOS.

Island Group	Population	Number of populated islands	Total in-service international/mainland connections	Total international/mainland connections including planned cables	Distance from closest repair hub (km)
Azores	250,000	9	2	8	2342
Balaeric	1,100,000	4	5	5	604
Baltic	30,000	17	21	22	288
Canary	2,200,000	8	7	7	1644
Channel	170,000	5	6	6	124
Faroe	53,000	17	2	2	1373
Greek	10,500,000	227	13	16	1146
Hawaii	1,400,000	8	13	18	4202
Lofoton	24,000	7	2	2	1209
Mayotte	300,000	1	3	3	3320
Reunion	896,000	1	6	6	4022
Shetland	23,000	11	3	3	1107
Mean values for non-SIDS/LOS	**1,412,167**	**26**	**6.92**	**8.17**	**1782**
Barbados	290,000	1	4	4	1319
Cabo Verde	525,000	9	3	3	207
Comoros	850,000	3	4	4	3262
Fiji	940,000	100	8	12	6628
Guam	170,000	1	15	21	2185
Jamaica	2,900,000	1	5	5	928
Maltese	520,000	2	5	6	191
Montserrat	5000	1	1	1	1133
Palau	18,000	5	1	2	1014
Papua New Guinea	9,000,000	200	2	3	2583
Solomon Islands	750,000	100	1	2	4199
St Vincent and the Grenadines	110,000	9	4	4	1127
Tonga	106,000	7	1	2	751
Vanuatu	310,000	65	1	2	5577
Mean values for SIDS/LOS	**1,178,143; 576,000 (excl. Papua New Guinea)**	**36**	**3.93**	**5.07**	**2222**

Repairs to the subsea cable (or land-based infrastructure) may also be complicated by other events, for example active or ongoing natural hazards or conflicts. A subsea cable repair requires a vessel on location for a period of typically at least a few days, able to hold position reliably. Events such as continuing volcanic activity, storminess, conflicts or political instability may limit the ability of a vessel to accomplish this, either by physically presenting a risk to the repair vessel, or due to an inability to get the permits required to conduct a repair. Based on our analysis, this is particularly relevant for volcanic islands and those that lie in the South Pacific, Indian Ocean and parts of the North Atlantic, which are more prone to these natural hazards. In all regions, small islands exposed to generally high windspeeds or regular storms, may find cable repairs additionally challenging. All islands, and in fact all nations, could experience challenges associated with public disorder or conflict and these events can both present an increase in hazard for telecommunications and pose a challenge to repairs.

These considerations highlight that telecommunications resilience in small island settings must adopt a whole-of-system perspective, encompassing not only subsea infrastructure but also terrestrial assets, institutional capacity, and the broader socio-political environment [64]. Consequently, building resilience requires not only technical redundancy, but also investments in governance, preparedness, and regional cooperation to address the structural vulnerabilities associated with smallness, remoteness, and exposure to external shocks [63].

4.5. Resilience and specific challenges for Small Island Developing States/Large Ocean States

We now discuss some of the specific aspects of resilience and challenges that are distinct to Small Island Developing States/Large Ocean States. SIDS/LOS typically share many of the same challenges, including a vulnerability to climate change and natural hazards, isolation, and economic fragility [68]. While some of these challenges may be shared with other islands, non-SIDS/LOS are more economically resilient to natural hazards and other disasters. The small size, isolation, and limited resources of SIDS mean they often have single points of failure in their telecommunications systems, potentially making them more vulnerable than other islands to outages and complicating and delaying repairs. These structural constraints are well recognised in the broader SIDS literature, where limited economies of scale, remoteness, and exposure to external shocks combine to reduce system redundancy and adaptive capacity (e.g. Ref. [62]).

For all the case study islands we identified the number of international and/or mainland connections the island or island group had from the global Telegeography cable database, and we also calculated their straight-line distance from the nearest home port of a cable repair vessel (Table 2). Overall, islands that are classified as SIDS/LOS had fewer international/mainland connections (on average 3.9 for SIDS/LOS versus 6.9 for other islands) and lay further away from repair vessel hubs (2200 km for SIDS/LOS versus 1800 km for other islands). The SIDS/LOS also had twice as many islands with two or fewer international connections than the other group. Both of these factors make SIDS/LOS more vulnerable to telecommunications outages. Having fewer subsea cable connections and/or a lack of geographic variability in routes reduces telecommunications resilience as subsea cable damage may cause an outage or substantial loss of bandwidth. Being further away from repair vessel hubs requires a longer transit for repair ships to reach the region, lengthening the potential outage duration. This is consistent with broader observations that remoteness and small market size constrain both infrastructure investment and the speed of recovery following disruption [62].

The importance of geographic diversity of routes is well illustrated by comparing the 2024 magnitude 7.3M_w earthquake in Vanuatu discussed above and the 2024 7.4M_w earthquake in Taiwan. While Vanuatu relies on a single international connection to Fiji, Taiwan has 26 subsea connections to the global internet. Unlike Vanuatu, where damage to the cable landing station resulted in a full telecommunications outage for nine days, in Taiwan, despite power disruption to 172 base stations [69], disruption lasted less than an hour, after which internet traffic was back up to 5% above normal [15,66,70]. This comparison highlights how redundancy and network diversity, which are more feasible in larger systems and wealthier nations, fundamentally underpin resilience outcomes [71].

SIDS/LOS may present particular challenges for cable repair. The ability to respond effectively to subsea cable faults is influenced by several logistical, environmental, and resource-related factors. While repair processes are generally efficient, emerging pressures from climate change [72], growing network length, and limited regional capacity highlight the need for strategic investment and coordination, which may result in longer repair times when cable faults occur [73,74]. The key factors affecting repair times are.

1. Distance and access: The wide geographic dispersion of nations can result in long transit distances between faults and repair depots or home ports. These distances remain a key determinant of repair time.
2. Permitting: Permit requirements vary by jurisdiction and changes in regulation can inadvertently add time and complicate repair operations.
3. Weather and Environmental Challenges: Severe weather and changing ocean conditions can delay repair operations. The effects of climate change (such as more frequent tropical storms and adverse sea conditions) can extend the duration of outages and complicate vessel operations.
4. Vessel and Spare Cable Availability: Vessel availability is typically good; however, simultaneous faults or cable ship deployment to operations unrelated to cable repair (e.g. installing another cable) can create challenges. Spare cable availability is another challenge. The decision to stock spare lengths of cable as well as other components such as repeaters, which is usually based on a percentage of system length (typically informed by historical instances of faults/the perceived risk profile) and on a cost-benefit assessment by system owners. Events such as the 2022 Hunga Volcano eruption, which led to damage to almost 200 km of cable [9], highlight the vulnerability created by limited regional spare capacity, and if concurrent events were to occur in a region this would be significant.

5. Regional Repair Capacity and Future Demand: A recent report [75] suggested that the Pacific repair fleet, in its current configuration, lacks sufficient capacity to meet forecast growth in subsea cable routes and the expected increase in repair requirements. By contrast, the Atlantic region is forecast in the same report to have adequate vessel coverage for projected expansion.

The number of new subsea cable connections that are currently planned for SIDS/LOS (15 new systems planned for the 13 islands/groups) is the same as that for the non-SIDS/LOS (15 systems planned for the 12 islands/groups) ([4]; Table 2) that we assessed in this study. The new routes will provide much-needed resilience, with second connections planned for Tonga, Palau, Solomon Islands and Vanuatu; however, the focus of route expansion remains biased towards existing regional hubs in the South Pacific (i.e. 6 new connections planned for Guam and 4 for Fiji, which already have 15 and 8 connections respectively). This concentration reflects broader patterns of infrastructure investment, where hubs with existing connectivity and market demand continue to attract disproportionate development.

While subsea cables bring multiple social benefits, making the case for additional connections in SIDS/LOS can be challenging. Their lower (and often dispersed) populations mean there can be challenges in developing a purely economic business case for more than one connection. For example, SIDS/LOS considered in this study have a population of 576,000 on average (excluding Papua New Guinea) compared to 1,400,000 for non-SIDS/LOS island and island groups. As the initial investment is often too large for a single SIDS/LOS to bear, any business case tends to require regional (international) collaboration and public-private partnerships to share costs, which are frequently supported by government grants and international development financing to enable increased cable diversity. This aligns with wider evidence that resilience-building in SIDS often depends on external support, regional cooperation, and strategies that extend beyond purely market-driven infrastructure development [63].

4.6. Recommendations for telecommunications resilience based on regional and typological differences

The data presented here reveal regional and typological differences between the exposure and causes of damage to subsea cables that connect small islands. The primary difference in exposure was between volcanic and non-volcanic islands, although other regional differences do exist. Non-volcanic islands experience a much higher exposure to anthropogenic faults, while volcanic islands are more exposed to natural hazards. Given the close correlation between exposure and fault occurrence for anthropogenic faults, recommendations for these islands, which are primarily in the North Atlantic and Mediterranean, should focus on reducing the risk from anthropogenic activity. While this typically involves appropriate protection measures, such as burial where possible, there is a limit to which physical protection can continue to work in regions where potentially damaging activity is persistent. It is likely equally, if not more important, particularly in regions that have historically not featured cable routes, to provide education and knowledge sharing

Table 3
Strategies to enhance telecommunications resilience for different island types.

Island Type	VOLCANIC ISLANDS
Dominant Hazard Exposure	Natural hazards — volcanic eruptions and associated hazards, earthquakes, submarine landslides, turbidity currents, and storms
Primary Vulnerabilities	Exposure to extreme, low-frequency events; rugged seafloor; complex nearshore bathymetry; synchronous damage to multiple cables
Recommended Resilience Strategies	• Improve geohazard mapping and monitoring (volcanoes, slope stability, seafloor sediment flows). • Optimise cable routing and stand-off distances using detailed bathymetry and understanding of processes. • Develop emergency satellite, microwave or other backup capacity. • Strengthen landing-station and power resilience to keep land-based infrastructure running.
Key Stakeholders/Actions	Telecommunication companies, fisheries agencies, port authorities, maritime regulators
Island Type	**NON-VOLCANIC ISLANDS**
Dominant Hazard Exposure	Anthropogenic hazards — fishing, anchoring, dredging, shipping; moderate storm and wave energy
Primary Vulnerabilities	High intensity of nearshore human activity; shallow shelves expose cables to abrasion and bottom trawling; frequent minor faults
Recommended Resilience Strategies	• Increase cable burial depth and physical protection in nearshore zones to below depth of influence of fishing gear and anchoring. • Strengthen coordination and awareness with fisheries and maritime sectors. • Deploy real-time AIS monitoring and potentially fibre-sensing to detect bottom-contacting vessel activity near cables. • Promote marine spatial planning that considers cable protection.
Key Stakeholders/Actions	Telecommunication companies, fisheries agencies, port authorities, maritime regulators
Island Type	**SMALL ISLAND DEVELOPING STATES/LARGE OCEAN STATES**
Dominant Hazard Exposure	Compound risks — both natural and anthropogenic, plus socioeconomic vulnerability
Primary Vulnerabilities	Few international connections; sometimes with dependence on single landing stations; limited local repair capacity; long distance from repair vessels
Recommended Resilience Strategies	• Increase route and landing diversity, which may be enabled through regional partnerships. • Climate-Resilient Planning: Repair and maintenance strategies should incorporate updated risk assessments that account for evolving weather patterns, natural hazards, changing human activities and the likelihood of multiple concurrent faults. • Establish shared cable maintenance agreements and pre-positioned cable spares. • Strengthen onshore infrastructure and backup power systems. • Seek development financing for redundancy and capacity building. • Integrate telecom resilience into national disaster risk frameworks.
Key Stakeholders/Actions	National governments, regional organizations, multilateral banks, development partners

about the existence of subsea cables, their importance and how and why to avoid them. In such discussions, building relationships with maritime industries is essential to support cooperation of both industries for mutually beneficial use of the marine area. New technologies may also assist with cable protection, including the growing use of sensing along the optical fibres that lie at the core of subsea telecommunications cables (e.g. [76]). In addition to detecting the effects of seafloor currents (e.g. strumming and abrasion), fibre sensing can be used to detect approaching fishing vessels or potentially harmful seafloor activities to alert companies of approaching vessels, such that intervention measures [76–78] can be put in place before damage is done or identify the vessel after damage, so that restitutions can be sought. However, outside of regions of national jurisdiction nations are limited in the actions they can take against foreign vessels or companies.

For those areas exposed to primarily natural hazards, including volcanic islands and islands in the South Pacific, North Pacific and Indian Ocean, which includes many SIDS/LOS, existing cable routing and protection measures appear to be largely effective at protecting cables from normal ocean conditions and day-to-day hazards. However, extreme events, such as major storms, volcanic eruptions, earthquakes, large landslides and seabed flows, while less frequent, present a much greater hazard for subsea cables, with potential to damage several cables synchronously or large lengths of cable, complicating repairs (e.g. [1,9,32]). Better understanding of the spatial and temporal recurrence of these extreme events is required, in order to better understand where these may be a threat to planned cable systems within the cable lifetime. Every effort should be, and typically is, made to avoid these hazards, however, where they cannot be avoided, it may be possible to identify safer stand-off distances based on a better understanding of the conditions present and their reach during such events. Again, fibre sensing could also be used to forecast some such events. While this would not allow all hazards to be fully avoided, warning could allow additional time to provide alternative telecommunications coverage. For natural hazards, it is also important to be aware that the seafloor infrastructure is only one part of the system, resilient land-based infrastructure, in particular back up power systems, should be made available to support telecommunications during and after extreme events.

For SIDS/LOS, while the greatest resilience is always going to be provided by geographically diverse cable routes, this is unlikely to be easy to justify financially for most states. However, resilience could be improved by strengthening land-based infrastructure (particularly power systems, as above), by increasing the availability of spare cable and its geographic distribution, and by improving the repair vessel and maintenance coverage, to support these states. In all cases additional support can be provided by low-level satellite coverage or land-based microwave networks, although these systems may also be impacted by natural events (e.g. volcanic ash) or disruption to power or land-based infrastructure. Table 3 summarises strategies that could enhance resilience for different island types.

5. Conclusions

This study provides the first global assessment of subsea telecommunications resilience for small islands, integrating a 40-year cable fault database with spatial analyses of environmental and anthropogenic hazard exposure across 24 island and island groups.

Three key findings emerge. First, cable faults are strongly concentrated in island-proximal environments, with more than 75% of faults on island-connected systems occurring within 300 km of coastlines. This demonstrates that the areas immediately surrounding islands represent disproportionately hazardous environments for subsea telecommunications infrastructure.

Second, the dominant drivers of cable damage differ systematically between island types and regions. Anthropogenic hazards, particularly fishing and anchoring, are responsible for the majority of faults globally and show a statistically significant relationship between exposure and fault occurrence. In contrast, no convincing significant relationship is observed between natural hazard exposure and faults, suggesting that engineering design and route selection are generally effective at mitigating routine environmental risks, although extreme events remain a significant threat.

Third, structural factors strongly influence resilience outcomes. Small Island Developing States (SIDS) and other remote island systems typically have fewer cable connections and are located further from repair capacity, increasing both the likelihood and duration of outages. These findings highlight that telecommunications vulnerability is shaped not only by hazard exposure, but also by network configuration and geographic isolation.

These results demonstrate that small islands represent a distinct class of infrastructure vulnerability, where high dependence on telecommunications, limited redundancy, and concentrated exposure to hazards combine to increase risk. Resilience strategies must be tailored to local conditions. For anthropogenically dominated environments, improved spatial planning, protection measures, and cross-sector coordination are critical, while for hazard-prone regions, system-level redundancy and contingency planning are essential. More broadly, strengthening resilience will require integrated approaches that combine engineering, governance, and international cooperation.

Several limitations should be acknowledged. The analysis is based on a finite sample of 24 island systems and a cable fault database that, while extensive, contains uncertainties in fault attribution and does not include the most recent events beyond 2019. Hazard exposure is assessed using proxy variables derived from global datasets of varying spatial resolution and aggregated within 300 km buffers, which simplifies complex local processes. In addition, statistical analyses are limited by relatively small sample sizes and the use of binary fault occurrence metrics. Consequently, the results should be interpreted as regional-scale patterns of relative vulnerability rather than precise, site-specific predictions. These limitations highlight several priorities for future research. Expanding global cable fault datasets to include more recent events and improving attribution of fault causes would strengthen statistical analyses. Higher-resolution, site-specific studies could better resolve local hazard processes and their interaction with cable routing and protection measures. In addition, integrating dynamic datasets (e.g. real-time vessel activity or environmental monitoring) may improve understanding of temporal variability in risk.

Finally, while this study focuses on subsea cable systems as the backbone of global telecommunications, there is increasing interest in complementary technologies that may enhance resilience during disruption events. Satellite-based communication systems, for example, can provide temporary or emergency connectivity when cable infrastructure is damaged, although they currently have limitations in bandwidth, latency, and cost compared to fibre-optic networks. Further research is needed to evaluate how hybrid systems combining subsea cables with satellite and other emerging technologies could improve redundancy and support rapid recovery in small island settings.

Despite these limitations, this study provides a new global framework for understanding telecommunications resilience in small island settings and highlights the need for targeted, context-specific strategies to safeguard these critical systems.

CRediT authorship contribution statement

Isobel A. Yeo: Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Michael A. Clare:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Conceptualization. **Matthew West:** Writing – review & editing, Formal analysis, Conceptualization. **Stuart Wilson:** Writing – review & editing, Conceptualization. **Lucy Bricheno:** Writing – review & editing, Formal analysis. **John Wrottesley:** Writing – review & editing, Conceptualization. **Keir Preedy:** Writing – review & editing, Conceptualization. **Paul Komboi:** Writing – review & editing, Conceptualization. **Lane Burdette:** Writing – review & editing, Formal analysis. **Taaniela Kula:** Writing – review & editing, Conceptualization. **Rennie Vaiomounga:** Writing – review & editing, Conceptualization. **Semisi Panuve:** Writing – review & editing, Conceptualization. **Camino Kavanagh:** Writing – review & editing, Conceptualization.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2026.106213.

Data availability

Data is open acess except for cable faults database which is confidential

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