Science of the Total Environment 852 (2022) 158356

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Strategic environmental sensitivity mapping for oil spill contingency planning in the Peruvian marine-coastal zone

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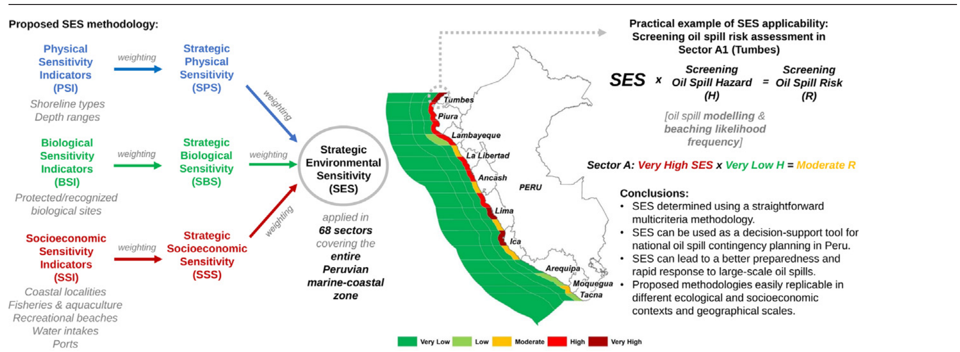
HIGHLIGHTS

- SES mapping as a decision-support tool for oil spill contingency planning.
- Highest SES levels found in northern and central coastal sectors of Peru.
- Oil spill risk levels can be obtained by relating the SES and the spill hazard.

GRAPHICAL ABSTRACT



ARTICLE INFO

Guest Editor: Julian Blasco

Keywords:
Oil spill
Sensitivity
Contingency planning
Marine-coastal zone

ABSTRACT

Major oil spills can cause significant impacts on marine-coastal zones, particularly on areas with a high oil spill risk, which combine a high oil spill hazard—high likelihood of oil stranding at high concentrations, and a high environmental sensitivity—high concentration of highly sensitive ecological and socioeconomic resources. In this context, a straightforward multicriteria methodology is proposed to determine the second factor of the oil spill risk, namely the strategic environmental sensitivity (SES), in 68 sectors covering the entire Peruvian marine-coastal zone. The methodology comprised the weighted integration of physical, biological, and socioeconomic sensitivity indicators based on their relevance in surface marine oil spills and the Peruvian ecological and socioeconomic context. As a result, relative SES levels from very low to very high were assigned to the sectors. To demonstrate the SES applicability, an oil spill risk assessment at a screening level was performed in a selected sector with current oil production activities. The oil beaching likelihood of worst-case discharge scenarios modelled for January 2021 was used to determine an overall screening oil spill hazard level in the selected sector, while a matrix relating the SES and hazard determined the screening oil spill risk. The results can be used as a decision-support tool to enhance the oil spill contingency planning in Peru or be used in other relevant processes such as the integrated coastal zone management, the marine spatial planning, or the contingency planning of other liquid contaminants. In addition, the proposed methodologies can be adapted to different local and international contexts and scales.

1. Introduction

Major accidental oil spills can cause significant ecological and socioeconomic impacts on marine-coastal zones. A clear example on the matter is the Deepwater Horizon oil spill in the Gulf of Mexico in 2010 which caused the oiling of thousands of kilometers of shoreline, the death of more than a

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http://dx.doi.org/10.1016/j.scitotenv.2022.158356
Received 23 February 2022; Received in revised form 4 July 2022; Accepted 24 August 2022
Available online 29 August 2022

million biological organisms, and more than US$ 20 billion in economic losses (NRDC, 2015; NOAA, 2017). In this context, the use of tools that help reduce the overall oil spill risk of an operation, country, or region becomes essential. These tools should aim to support the oil spill contingency planning (OSCP) for the preparedness and rapid response to large-scale events (>5000 barrels) whose areas of potential impact can cover from national to international territories, and where the decision-making process of what to protect or clean up first is a difficult task.

One decision-support tool often used by the oil industry is the environmental sensitivity maps. For the oil industry, the environmental sensitivity to oil spills is defined as those marine-coastal features that hold an ecological, economic, or cultural importance; are at risk of exposure to the spilled oil; and are affected once they are oiled (Michel et al., 1994). The concept of sensitivity to oil spills is managed differently than the concept of vulnerability to oil spills. While the second involves the likelihood of exposure of a feature to an oil spill event, the first assumes that the feature will be exposed to oil and describes the relative effect of that exposure (e.g., deep corals may be sensitive to oil but not vulnerable to a surface marine oil spill, and rocky shores may be vulnerable but not sensitive) (IPIECA and IOGP, 2015b).

Environmental sensitivity maps have been adapted over the years to assist both responders and decision-makers according to their needs and the spill tiers (IPIECA et al., 2012). Currently, three types of environmental sensitivity maps are used: tactical, strategic, and operational. While tactical maps locate and describe the sensitive ecological and socioeconomic features to oil spills in an area of potential impact, strategic maps determine the most sensitive locations and help strengthen the response strategy in high-risk areas—those with a high oil spill hazard and a high environmental sensitivity. Finally, operational maps show specific information on how to deploy response resources in those high-risk areas. Nowadays, various environmental sensitivity mapping efforts are available in the literature, often following the guidelines proposed by the US National Oceanic and Atmospheric Administration (NOAA) (latest in Petersen et al., 2019) and international oil organizations (latest in IPIECA et al., 2012), but adapted to the local contexts in terms of stakeholders' values, drivers of change, data availability, technical

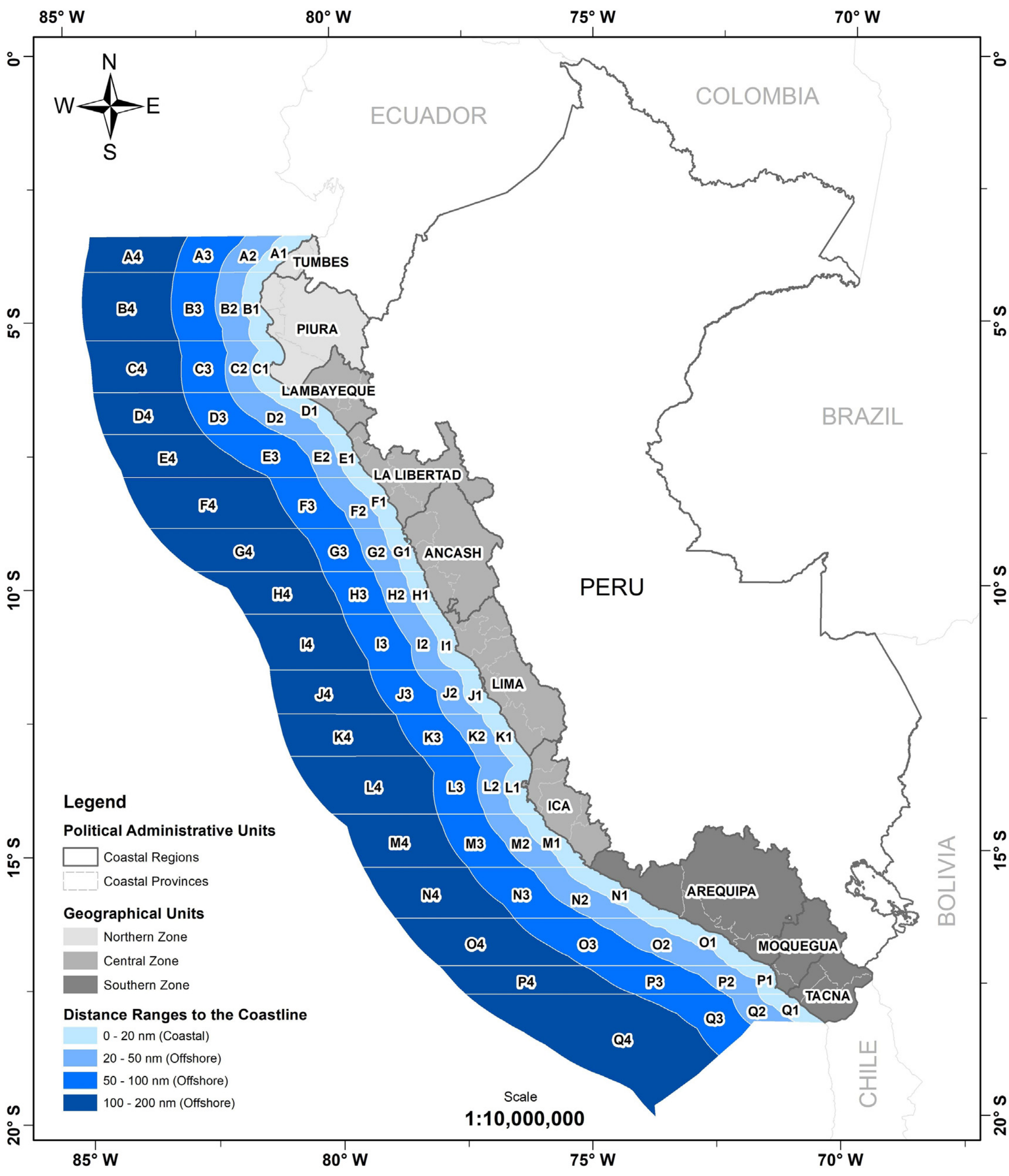

Fig. 1. Study area: the Peruvian marine-coastal zone divided into 68 sectors following political-administrative units and distance ranges to the coastline.

capacity of the users, and intended uses of the maps (NEA and UNEP-WCMC, 2019; Monteiro et al., 2020; Sardi et al., 2020; Feng et al., 2021).

Countries like Peru are not exempt from being affected by a major oil spill event at any time. In fact, current and forthcoming oil-related activities in the Peruvian marine-coastal zone such as the oil exploration and production and maritime traffic represent a latent threat to several sensitive features (Perupetro, 2021; UNCTADSTAT, 2021). Some of these features include a highly biodiverse and productive sea influenced by upwelling processes and a coastline with wetlands, bays, islands, islets, capes, and beaches with high biological diversity. Likewise, various marine-coastal socioeconomic activities such as small-scale and industrial fishing, mariculture, coastal tourism, maritime transport, among others, are relevant for food security, national economy, national and international trade, and overall, for the welfare of the population (MINAM, 2015).

Regarding the environmental sensitivity mapping in Peru, some efforts have been carried out. At a local level, maritime operators must hold information on sensitive features and priority protection sites around their facilities in case of worst-case oil spill scenarios. This information must be included in their internal OSCPs, as required by the General Directorate of Captaincies and Coastguards (DICAPI)—a department of the Peruvian Navy—in Directorial Resolution No. 0497-98/DCG. At a national level, the National OSCP contains tactical sensitivity maps prepared by DICAPI in 2005. Although these maps cover the entire Peruvian marine-coastal zone, information is scarce, and the maps only show sensitive biological and socioeconomic features, leaving aside the physical aspect. In addition, no strategic sensitivity mapping effort has been carried out at a national level up to date. It is therefore deemed necessary to determine the strategic environmental sensitivity (SES) in the entire Peruvian marine-coastal zone, i.e. to determine the relative sensitivity level to oil spills of different marine-coastal sectors, aiming to identify those most sensitive sites that require special attention during the OSCP process and reduce as low as reasonable possible the consequences from major oil spill contingencies.

2. Materials and methods

This work was divided into two main sections: the assessment of the strategic environmental sensitivity (SES) in the entire Peruvian marine-coastal zone, and a practical example of the applicability of the SES results through the assessment of the oil spill risk at a screening level in a selected sector of the study area.

2.1. Strategic environmental sensitivity (SES) assessment

2.1.1. Sectorization of the study area

The study area is the entire Peruvian marine-coastal zone, which comprises a coastline of 3080 km and a maritime domain of 200 nautical miles wide. It was divided into 68 sectors considering political-administrative units and distance ranges to the coastline. Sectors were coded in alphabetical order from north to south, and in numerical order from east (coastline) to west (offshore) (Fig. 1).

Table 1
Sensitivity indicators per environmental component.

Component	Indicator	Definition	Construction Criteria	Formula
Physical	PSI_1: Shoreline types	Intertidal habitats (NOAA's Environmental Sensitivity Index – ESI in Petersen et al. (2019)). Based on this 10-level scale, sheltered shorelines with low hydrodynamic energy and high associated biological productivity represent the most sensitive intertidal habitats.	Sectors with greater lengths of more sensitive shoreline types (ESI) are more sensitive than others.	$\frac{\Sigma(L_i \times RSL_i)}{L_S}$ *L*: length of shoreline in km; *RSL*: 1 (ESI 1 and 2), 3 (ESI 3 and 4), 5 (ESI 5 and 6), 7 (ESI 7 and 8), 9 (ESI 9 and 10); *i*: shoreline type (ESI); *S*: sector
	PSI_2: Depth ranges	On-water habitats (near coastal and offshore waters).	Sectors with greater coverage of lower water columns are more sensitive than others.	$\frac{\Sigma(D_i \times RSL_i)}{D_S}$ *D*: number of pixels; *RSL*: 1 (>200 m), 3 (100–200 m), 5 (50–100 m), 7 (20–50 m), 9 (≤20 m); *i*: depth range; *S*: sector
Biological	BSI_1: Protected/recognized biological sites	Nationally protected and internationally recognized marine and coastal biological sites, which involve several biological groups and habitats. Important biological sites still pending legal protection are also included.	Sectors with more coastal/shallower biological sites with a higher level of national protection and internationally recognized are more sensitive than others.	ΣRSL_i *RSL*: 1, 3, 5, 7, 9 (obtained by the combination of the protection level and the habitat type of the main conservation targets – Table 2); *i*: biological site
Socioeconomic	SSI_1: Coastal localities	Coastal population living within a 2-km buffer landward.	Sectors with a larger population are more sensitive than others.	P_S *P*: total coastal population; *S*: sector
	SSI_2: Fisheries and aquaculture – $SSI_{2.1}$: Fishing grounds	Areas where small-scale and industrial fishermen catch fish in the sea.	Sectors with larger small-scale fish capture volumes and greater industrial fishing fleet presence are more sensitive than others.	$\frac{RSL_{S,i}+RSL_{S,j}}{2}$ *RSL*: 1 (very low), 3 (low), 5 (moderate), 7 (high), 9 (very high); *i*: fish capture volume; *j*: fleet presence; *S*: sector
	$SSI_{2.2}$: Fish landing sites	Fixed coastal facilities where caught fish is managed and/or processed (small-scale fish landing facilities and fish processing plants).	Sectors with greater volumes of fish landings are more sensitive than others.	F_S *F*: average annual total fish landing volume in metric tons; *S*: sector
	$SSI_{2.3}$: Mariculture sites	Areas where marine organisms such as fan shells and shrimps are cultivated.	Sectors with more easily exposed mariculture sites are more sensitive than others.	ΣRSL_i *RSL*: 5 (inland - connected to the sea), 9 (at sea); *i*: mariculture site
	SSI_3: Recreational beaches	Both beaches and surfing sites visited by the population during summer. Surfing sites were included given their legal protection by Law No. 27280.	Sectors with a higher beach and surf importance assigned in official Peruvian tourism websites and plans and newspapers (Appendix A) are more sensitive than others.	$\frac{RSL_{S,i}+RSL_{S,j}}{2}$ *RSL*: 1 (very low), 3 (low), 5 (moderate), 7 (high), 9 (very high); *i*: beach importance; *j*: surf importance; *S*: sector
	SSI_4: Water intakes	Seawater extraction sites for several socioeconomic activities such as inland mariculture, fish processing, mining, oil refining, drinkable water supply, among others.	Sectors with a greater volume of seawater extracted are more sensitive than others.	V_S *V*: total volume of seawater extracted in tons per year; *S*: sector
	SSI_5: Ports	Maritime facilities where vessels dock to load and discharge passengers and cargo.	Sectors with more important ports are more sensitive than others.	ΣRSL_i *RSL*: 5 (secondary port - export only), 7 (main port - national and international commerce), 9 (main port of Peru - Callao); *i*: port

Table 2
Relative sensitivity levels (RSL) for BSI_1.

RSL	Protection level[a,b]			
Habitat type of the main conservation targets[c]	Municipal level OR international recognition	Regional level OR municipal level with international recognition	National level OR regional level with international recognition	National level with international recognition
Deep offshore habitat (e.g., seamounts, banks)	1	1	1	3
Subtidal habitat (only) (e.g., rocky reefs, banks)	1	3	3	5
Intertidal habitat (e.g., beaches, capes, islands, islets, including their subtidal influence)	1	3	5	7
Intertidal habitat (e.g., wetlands influenced by the sea)[d]	3	5	7	9

[a] Municipal: Environmental Conservation Area (ACA) and other municipal conservation sites; regional: Regional Conservation Area (ACR) and fragile ecosystems; and national: national reserves, national sanctuaries, wildlife refuges, reserved zones, national recovery sites. Reserve zones are areas whose protection category has not been assigned yet; nevertheless, the maximum protection level has been assigned to them in this assessment.

[b] International recognition: BirdLife's Important Bird Area (IBA), Ramsar Convention, UNESCO's biosphere reserve, Western Hemisphere Shorebird Reserve Network (WHSRN), or Pacific Shorebird Conservation Initiative (PSCI).

[c] A main conservation target refers to the biological group or species that is key for the wildlife conservation of a biological site. In case conservation targets are located in different habitats, the highest applicable RSL is assigned.

[d] Coastal wetlands separated from the sea were not included in the assessment.

2.1.2. Selection and construction of sensitivity indicators

A comprehensive data gathering and document review on publicly available online sources such as geoservers, databases, and reports from national authorities, international organizations, research institutes, NGOs, among others, was carried out to identify the main ecological and socioeconomic sensitive features to oil spills in the study area (Appendix A). Ten sensitivity indicators grouped into the physical, biological, and socioeconomic components (PSI_i, BSI_i, and SSI_i, respectively) were finally selected (Table 1). Sensitivity indicators were constructed based on the availability of data and the criterion that the more highly sensitive features present on a sector, the more sensitive that sector will be (Tables 1 and 2). When necessary, to differentiate the sensitive features within each sensitivity indicator, a relative sensitivity level (RSL) value was assigned (1, 3, 5, 7, and 9), where 1 refers to the least sensitive feature and 9 to the most sensitive, following the theoretical framework on marine oil spills and the Peruvian ecological and socioeconomic context.

Given the different scales and units used in the sensitivity indicators, raw results per sensitivity indicator were normalized by constructing five class intervals with the non-null minimum and maximum result among all sectors and by using a categorical-numerical scale: very low (1), low (3), moderate (5), high (7), and very high (9). Sectors with a null result were automatically assigned a null value (0). In addition, outliers were identified using the interquartile range prior normalization and then assigned the corresponding lowest (1) or highest scale value (9) (Appendix B).

Table 3
Weights assigned to sensitivity indicators per W_j.

Component	Indicator	W_1	W_2[a,b,c]
Physical	PSI_1	50 %	75 %
	PSI_2	50 %	25 %
	Total	100 %	100 %
Biological	BSI_1	100 %	100 %
	Total	100 %	100 %
Socioeconomic	SSI_1	20 %	10.94 %
	SSI_2	20 %	36.83 %
	$SSI_{2.1}$	33.33 %	58.13 %
	$SSI_{2.2}$	33.33 %	10.96 %
	$SSI_{2.3}$	33.33 %	30.92 %
	Sub-total	100 %	100 %
	SSI_3	20 %	20.64 %
	SSI_4	20 %	20.64 %
	SSI_5	20 %	10.94 %
	Total	100 %	100 %

[a] Intertidal habitats hold a higher ease of exposure to oil and a higher likelihood of impact than on-water habitats, though some exceptions can be found in coastal shallow and calm waters (Michel et al., 1994; IPIECA and IOGP, 2015b). In that sense, PSI_1 is considered moderately more important than PSI_2.

[b] The fisheries and aquaculture indicator (SSI_2) was assigned the highest weight since it represents highly important activities for coastal populations along the entire Peruvian coast (Guevara-Carrasco and Bertrand, 2017; IPIECA and IOGP, 2015a); in addition, these two activities represent around 1.3 % of the national gross domestic product (GDP) (INEI, 2020). Following in importance, both the recreational beaches indicator (SSI_3) and the water intakes indicator (SSI_4) were assigned the same weight. The first represents sun-and-beach tourism in Peru which accounts for 25 % of the total touristic activity in Peru (PromPerú, 2020a, 2020b), while the second represents the seawater resource required to carry out socioeconomic activities of high revenue (e.g., mining, oil refining) and of high social impact (e.g., inland mariculture and water consumption). Finally, the ports indicator (SSI_5) and the coastal localities indicator (SSI_1) were assigned the lowest weight since ports hold an organizational structure and resources to manage contingencies, while the main socioeconomic resources and activities of coastal populations are addressed in the sensitivity indicators before mentioned.

[c] When an oil spill occurs, fishing grounds are closed; consequently, fish landings decrease. Given this dependency, $SSI_{2.1}$ is considered strongly more important than $SSI_{2.2}$. Likewise, since the small-scale and industrial fisheries are a more developed activity along the entire Peruvian coast than mariculture, and since mariculture sites hold a higher ease of exposure given its fixed location in coastal shallow and calm waters (mostly bays), $SSI_{2.1}$ is considered only slightly more important than $SSI_{2.3}$. Finally, following transitivity and consistency, $SSI_{2.3}$ is considered moderately more important than $SSI_{2.2}$.

2.1.3. Calculation of the strategic sensitivity per environmental component

The strategic sensitivity of the physical, biological, and socioeconomic components per sector (SPS_j, SBS_j, and SSS_j, respectively) was obtained through the weighted sum of their respective normalized sensitivity indicators (N_{PSIi}, N_{BSIi}, N_{SSIi}). Two weighting scenarios (W_j) were considered: (W_1) sensitivity indicators hold an equal weight (conservative scenario) among them in their corresponding component, and (W_2) they hold different weights based on the theoretical framework on surface marine oil spills and the Peruvian ecological and socioeconomic context (Table 3). The Analytical Hierarchy Process (AHP) proposed by Saaty (1987) was used for the weighting process, as suggested in the Handbook on Constructing Composite Indicators by OECD (2008). The AHP comprised ordinal pairwise comparisons through matrices, asking which sensitivity indicator was more

Table 4
Weights assigned to the strategic sensitivities of the environmental components per W_k.

Strategic sensitivity	W_A	W_B	W_C	W_D
SPS	33.33 %	60 %	20 %	20 %
SBS	33.33 %	20 %	60 %	20 %
SSS	33.33 %	20 %	20 %	60 %
Total	100 %	100 %	100 %	100 %

Table 5
OSS modelled in sector A1 (Tumbes).

Code	Spill source	Scenario	API	Spill type	Volume	Simulation length
OSS1	Corvina CX-11 and CX-15 platforms and wells	Well blowout	30°	Continuous	250 tph × 168 h	168 h
OSS2	Albacora Z1-8-A platform and wells	Well blowout	30°	Continuous	250 tph × 168 h	168 h
OSS3	Peña Negra PN10 platform and wells (closest active production well to sector A1)	Well blowout	30°	Continuous	250 tph × 168 h	168 h
OSS4	Corvina FSO and multibuoy terminal	Fire and explosion	30°	Instantaneous	15K tonnes	168 h
OSS5	Albacora FSO and multibuoy terminal	Fire and explosion	30°	Instantaneous	15K tonnes	168 h
OSS6	Oil tanker 1 (towards refinery)	Fire and explosion	30°	Instantaneous	50K tonnes	168 h
OSS7	Oil tanker 2 (towards refinery)	Fire and explosion	30°	Instantaneous	50K tonnes	168 h
OSS8	Oil tanker 3 (towards refinery)	Fire and explosion	30°	Instantaneous	50K tonnes	168 h
OSS9	Oil tanker 4 (towards refinery)	Fire and explosion	30°	Instantaneous	50K tonnes	168 h
OSS10	Oil tanker 5 (towards refinery)	Fire and explosion	30°	Instantaneous	50K tonnes	168 h

important than the other using a scale from 1 (equally important) to 9 (extremely more important). Each matrix was then normalized to obtain the corresponding weights of each sensitivity indicator so that the sum of weights is 100 %. To guarantee transitivity and non-contradictory results, the consistency ratio did not exceed 10 %. Raw results were then normalized using the same categorical-numerical scale as with the sensitivity indicators (Appendix B).

$$SPS_j = \Sigma(N_{PSI\,i} \times W_{i,j})$$

$$SBS_j = \Sigma(N_{BSI\,i} \times W_{i,j})$$

$$SSS_j = \Sigma(N_{SSI\,i} \times W_{i,j})$$

2.1.4. Calculation of the strategic environmental sensitivity (SES)

The Strategic Environmental Sensitivity (SES_k) per sector was obtained through the weighted sum of the normalized strategic sensitivities per environmental component (N_{SPS_j}, N_{SBS_j}, N_{SSS_j}). Four weighting scenarios (W_k) were considered: (W_A) $SPS = SBS = SSS$ (conservative scenario); (W_B) $SPS > SBS = SSS$; (W_C) $SBS > SPS = SSS$; (W_D) $SSS > SPS = SBS$ (Table 4). The AHP was used for the weighting process. Raw results were then normalized using the same categorical-numerical scale as with the sensitivity indicators. The final SES (SES_{final}) per sector was obtained through the average of all normalized SES results (N_{SES_k}) (Appendix B).

$$SES_k = \left(N_{SPS_j} \times W_k\right) + \left(N_{SBS_j} \times W_k\right) + \left(N_{SSS_j} \times W_k\right)$$

$$SES_{final} = average\left(N_{SES_k}\right)$$

2.2. Screening oil spill risk (R) assessment

2.2.1. Selection and modelling of worst-case discharge oil spill scenarios

The northern coastal sector A1 (Tumbes) was selected as the modelling site since offshore oil production activities are currently carried out in it. Ten worst-case discharge oil spill scenarios (OSS) from these activities

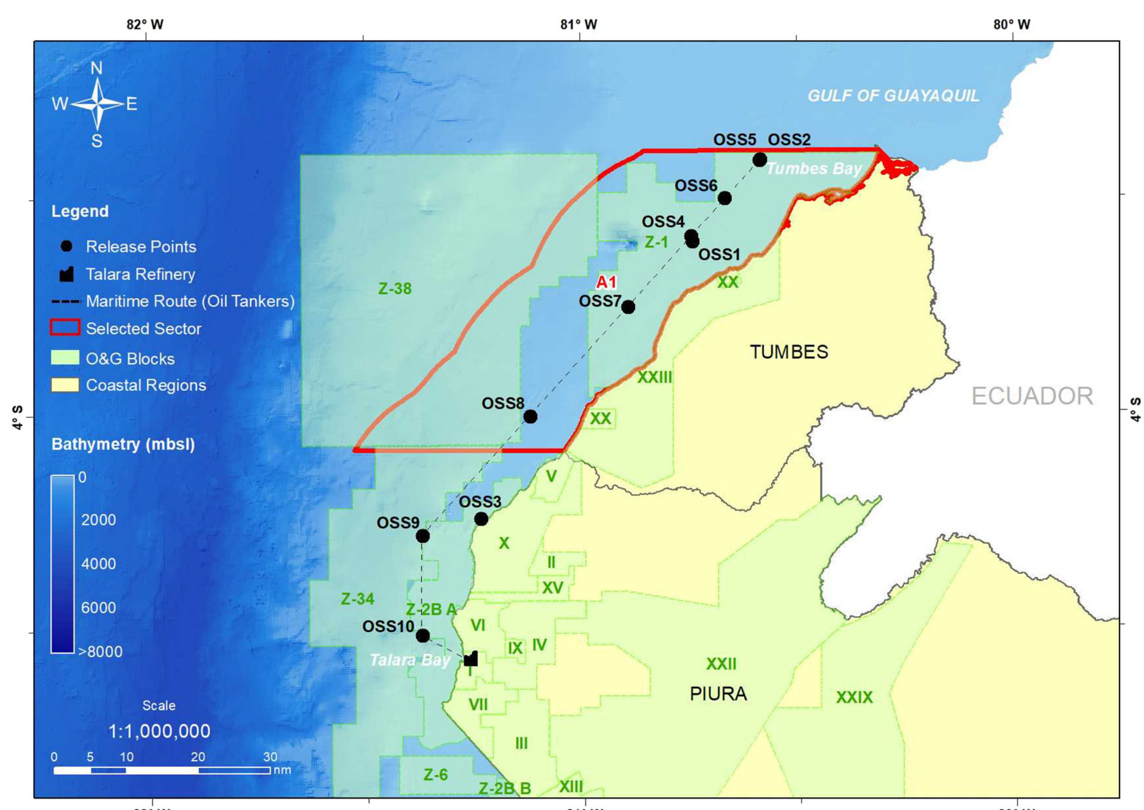

Fig. 2. OSS release points in sector A1 (Tumbes).

Table 6
Model parameters set-up on MEDSLIK-II.

Parameter	Value
Stokes' drift	No
Wind correction	1 %
Horizontal diffusivity coefficient	10 m^2/s
Evaporation rate	0.00008 m/s
Dispersion rate	0.000008 l/s
Thick slick spreading rate	150 l/s
Oil parcel number	90,000 #

were modelled for a single month and year considering the screening level of the assessment (Table 5 and Fig. 2). The activities modelled were (a) the oil extraction in platforms and associated wells, (b) the oil storage in FSOs (floating storage and offloading units), which then offload oil through multibuoy mooring systems to tankers, and (c) the oil transportation through tankers from the platforms in Tumbes to the Talara Refinery in Piura. OSS were run for January 2021 given the relevance of the summer season in ecological patterns and socioeconomic activities in northern Peru.

The API gravity for all scenarios was set at 30°, which represents a rough average for the Corvina, Albacora, and Peña Negra oil fields (Perupetro, 2010; BPZ, 2016; Savia Peru, 2020). Well blowout scenarios assumed the uncertainties due to subsurface conditions since production wells are located at depths below 50 m and at distances to the coastline of <10 nm; likewise, the spilled volume from these scenarios was set at 250 tonnes per hour (tph), which represents the roughly rounded average of shallower coastal OSS set by the US Bureau of Safety and Environmental Enforcement (BSEE) for offshore drilling in the US Outer Continental Shelf (OCS) (Buchholz et al., 2016). Regarding the FSO and oil tanker fire and explosion scenarios, the spilled volume was set at 15K and 50K tonnes, respectively. The first represents the maximum FSO storage capacity used in Block Z-1 (Pacific Rubiales, 2014; MINEM, 2018; Savia Peru, 2020) while the second represents the maximum storage capacity of Peruvian-flagged oil tankers (Histamar, 2020).

OSS were modelled on MEDSLIK-II, a freely available Lagrangian model for short-term forecasting of marine surface oil spills following the model parameters set-up in Table 6. Model parameters set-up on MEDSLIK-II (De Dominicis et al., 2013a, 2013b; Sepp-Neves et al., 2016, 2020). To include the effect of the variability of metocean conditions, OSS were modelled every three days, reaching a total of eleven 7-day (168 h) simulations run per OSS. Oceanographic data derived from the 1/12° hourly global surface analysis fields of the Copernicus Marine Environment Service (CMEMS) and atmospheric data from the 1/10° 6-h High-Resolution global model (HRES) of the European Center for Medium-Range Weather (ECMWF).

2.2.2. Calculation of the screening oil spill hazard level (H)

The methodology proposed by Lyubartseva et al. (2015) was simplified to obtain an overall screening oil spill hazard level (H) for the whole sector A1. As a result, the likelihood frequency of oil beaching events (B) in sector A1, expressed as the oil stranding probability considering all simulations run for January 2021 for all OSS (M = 110), was applied (Appendix B). Beaching events were selected since they represent the greatest threats to sensitive features in the marine-coastal zone. A beaching event was a positive count when the spill, after the 168 simulation hours, covered a coastline of more than 1 km regardless of the stranded oil concentrations. Finally, H ranged between 0 and 1 based on a simple scale where 0 indicates no hazard and 1 a maximum hazard (Table 7).

$$H = \frac{1}{M} \times \sum_{0}^{M} B$$

Table 7
Screening oil spill hazard (*H*) scale.

Screening oil spill hazard level (*H*)	Description
[0.0, 0.2>	Very low
[0.2, 0.4>	Low
[0.4, 0.6>	Moderate
[0.6, 0.8>	High
[0.8, 1.0]	Very high

Table 8
Oil spill risk matrix.

		Strategic environmental sensitivity level (SES_{final})				
		Very low	Low	Moderate	High	Very high
Screening oil spill hazard level (*H*)	Very low	Low	Low	Moderate	Moderate	Moderate
	Low	Low	Moderate	Moderate	High	High
	Moderate	Low	Moderate	High	High	Very high
	High	Low	Moderate	High	Very high	Very high
	Very high	Low	Moderate	High	Very high	Very high

2.2.3. Calculation of the screening oil spill risk level (R)

The screening oil spill risk level (R) was then determined by relating the screening oil spill hazard level (H) and the final strategic environmental sensitivity level (SES_{final}), following a 5 × 5 matrix (Table 8). The oil spill risk levels were based on the general risk matrix included in the European Commission Notice on Reporting Guidelines on Disaster Risk Management, Art. 6(1)d of Decision No 1313/2013/EU.

3. Results and discussion

3.1. Strategic environmental sensitivity (SES)

The highest number of sensitivity indicators with very high and high levels were found in sectors J1 (central Lima, 7), A1 (Tumbes, 6), B1 (northern Piura, 5), G1 (northern Ancash, 5), I1 (northern Lima, 5), and L1 (northern Ica, 5), all located in both the northern and central coastal zones of Peru (Fig. 3). After aggregating the sensitivity indicators per environmental component and applying the weighing scenarios, sectors J1 (central Lima), A1 (Tumbes), and L1 (northern Ica) stood out; the first due to a very high SPS and SSS and a high SBS, the second due to a very high SPS and a high SBS and SSS, and the latter due to a very high SBS and a high SPS and SSS (Fig. 4). On the other hand, after aggregating the strategic sensitivities per environmental component and considering all weighting scenarios (Fig. 5), it was found that northern coastal sectors, followed by central coastal sectors, obtained the highest SES, in contrast with southern coastal sectors and offshore sectors which obtained the lowest (Fig. 6). Specifically, sectors A1 (Tumbes), J1 (central Lima), and L1 (northern Ica) obtained the highest SES, confirming the well-known relevance of their ecological, socioeconomic, and scientific attributes, and validating the functionality of the SES methodology (Fig. 6).

For instance, sector A1 is recognized for its mangrove forests that sustain important inland mariculture activities and three protected areas internationally recognized: the Tumbes' Mangroves National Sanctuary and the Environmental Conservation Areas Tumbes River Delta and Puerto Pizarro Bay and La Chepa-Corrales. In addition, the unique tropical environment in northern Peru where sector A1 is located sustains a significant beach resort activity and supports the creation of the Grau's Tropical Sea National Reserve, still with pending legal protection but included in this assessment for technical purposes. Sector J1, on the other hand, involves the coastal populations of Lima—the capital—and holds the main port in Peru—the Callao Port. This sector also holds a great number of protected islets, islands, capes, and wetlands and is highly visited for beach and surf activities. Finally, sector L1 is known for the bays Pisco-Paracas and Independencia, which sustain the greatest number of mariculture sites in Peru and are considered beach and biological paradises at a national and

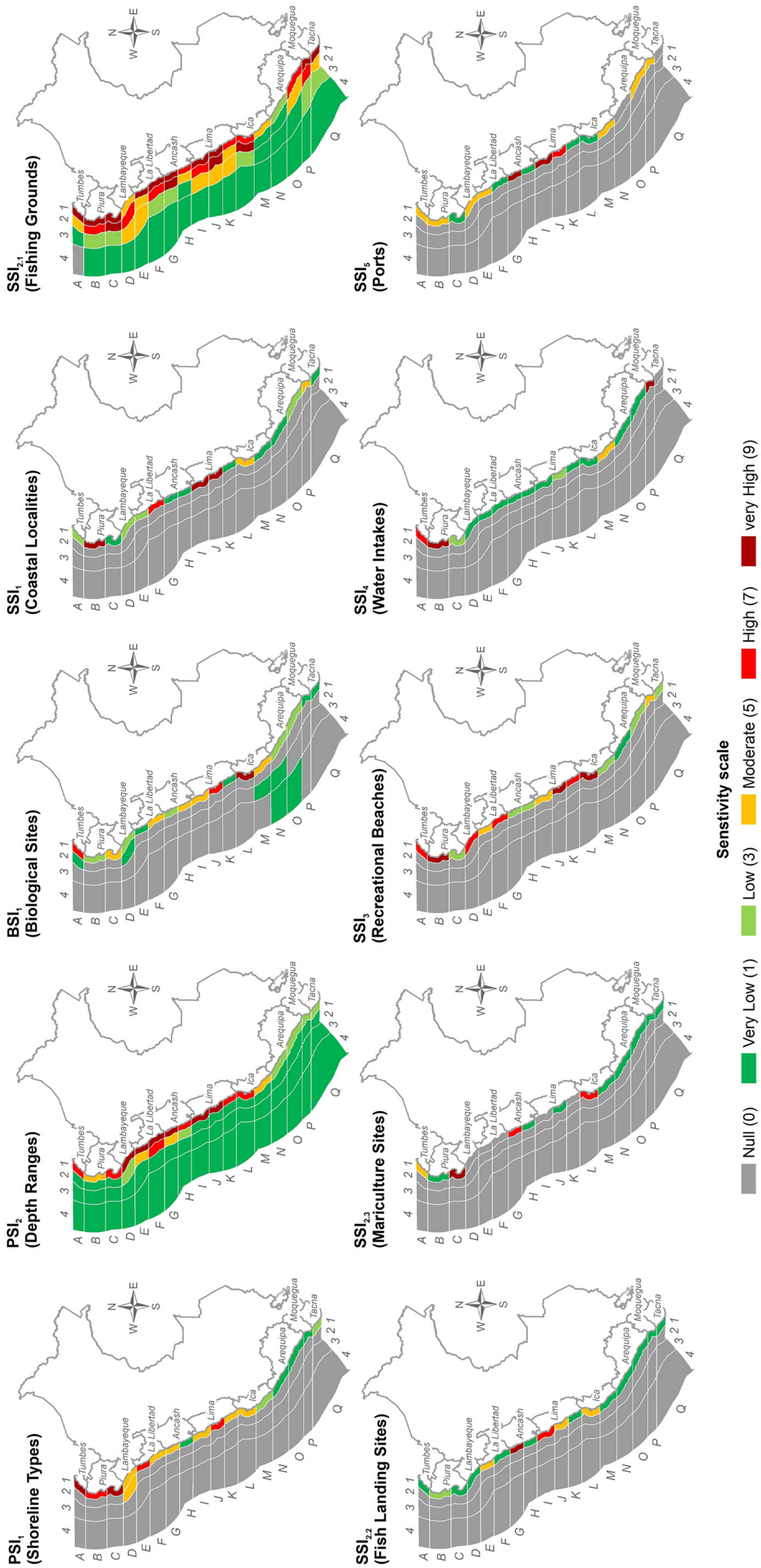

Fig. 3. Normalized results per physical, biological, and socioeconomic sensitivity indicator (PSI, BSI, and SSI, respectively).

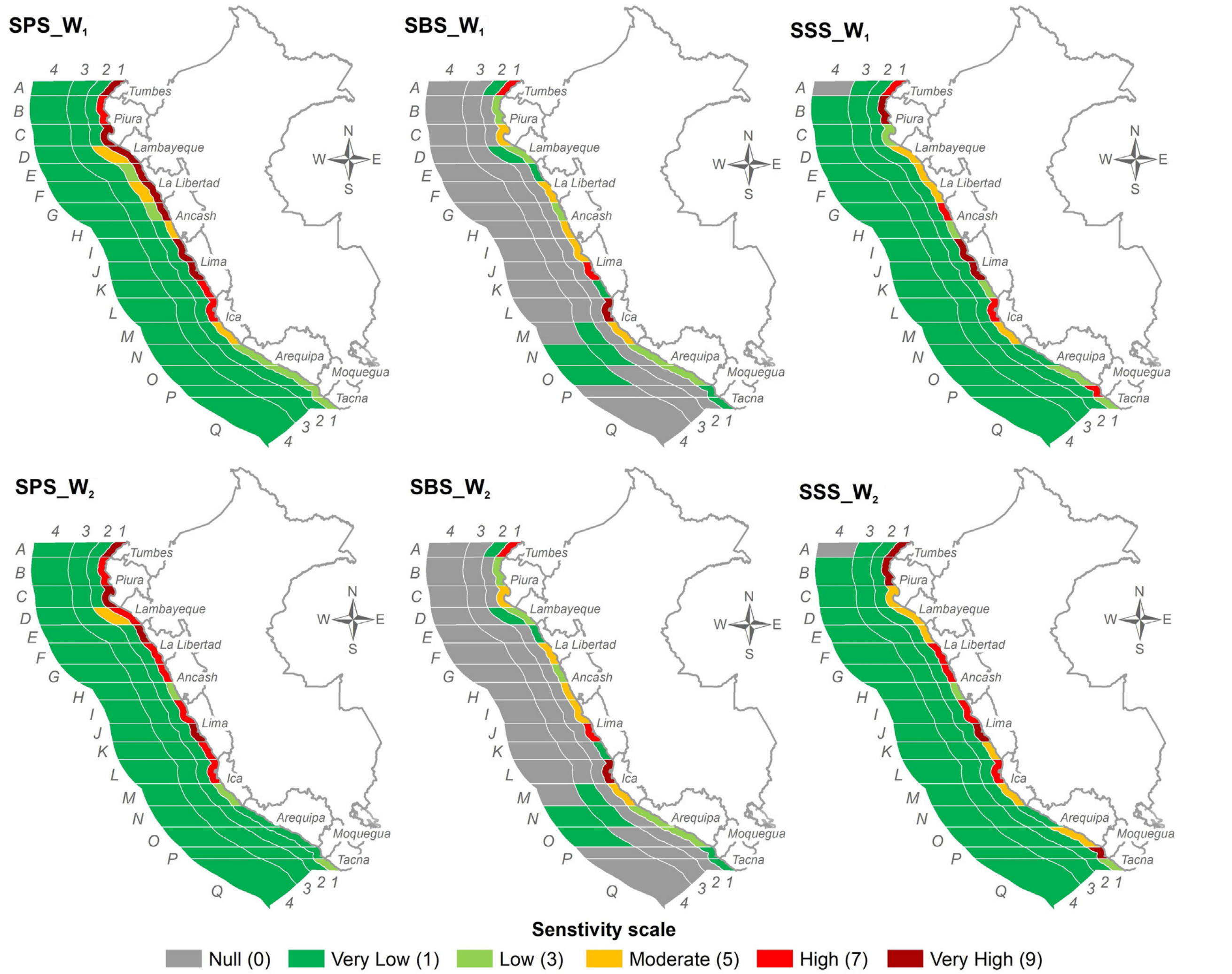

Fig. 4. Normalized results of the strategic physical, biological, and socioeconomic sensitivities (SPS, SBS, and SSS, respectively) per weighting scenario (W_j): equal (W_1) and different (W_2) weights assigned to sensitivity indicators within their corresponding environmental component.

international level. These two bays encompass the Paracas National Reserve and the Chincha and Ballestas National Reserves—the first being the most extensive marine-coastal protected area in Peru and also an IMO's Particularly Sensitive Sea Area (PSSA) due to its vulnerable ecological, socioeconomic, and scientific features to contingencies from international shipping activities.

The extensive documentation review and data gathering of the physical, biological, and socioeconomic components of the Peruvian marine-coastal zone allowed a deep understanding of its environmental sensitivity to oil spills. It also allowed the selection and construction of relevant independent sensitivity indicators, which were key to obtain a more accurate SES with the least duplicity of results. It is important to mention that although data was available online at a national level for most sensitivity indicators, some had to be created, rebuilt, or approximated. For example, the shoreline types (PSI_1)—one of the most critical features during sensitivity mapping efforts—were obtained through the reclassification of the general shoreline types established by the Peruvian Ministry of the Environment (MINAM) into NOAA's Environmental Sensitivity Index (ESI), carrying out for this purpose virtual verifications on Google Earth in >3000 km of shoreline. On the other hand, some indicators were constructed following a criterion beyond the presence or absence of sensitive features. One example is indicator BSI_1, which related the protection level and habitat type (ease of exposure to oil) of biological sites to differentiate the sensitivity level.

Sensitivity indicators can be improved, and other features could be added to enhance the SES assessment. For instance, the ground-truthing of the shoreline types (PSI_1) is recommended. In addition, indicator BSI_1 could be updated if new biological sites such as the BirdLife's marine IBAs or the IUCN's Important Marine Mammal Areas are identified in Peru. Furthermore, proxy indicators ($SSI_{2.1}$—fishing grounds and $SSI_{2.3}$—mariculture sites) could also be updated if temporal or spatial data becomes available. A seasonality factor could also be included given the well-known seasonal differences in the Peruvian fisheries and aquaculture (SSI_2) and beach tourism (SSI_3). Likewise, a coping capacity indicator describing the preparedness of oil and gas organizations and governments at all levels, the availability of response materials and equipment, among others, could also be added.

The assignment of weights to the sensitivity indicators and environmental components, framed under the Peruvian ecological and socioeconomic context, was also essential for a more realistic SES assessment. Participatory methods incorporating various stakeholders (experts, citizens, and politicians) could enhance the weighting process. Weighting criteria such as the urge or ease for response action (protection and clean-up) agreed by stakeholders could also be applied.

Normalization using intervals and a categorical-numerical scale, and the management of outliers were pertinent to ease the comparison between sectors regarding their results per sensitivity indicator, strategic sensitivity per environmental component, and the final SES. Normalized results

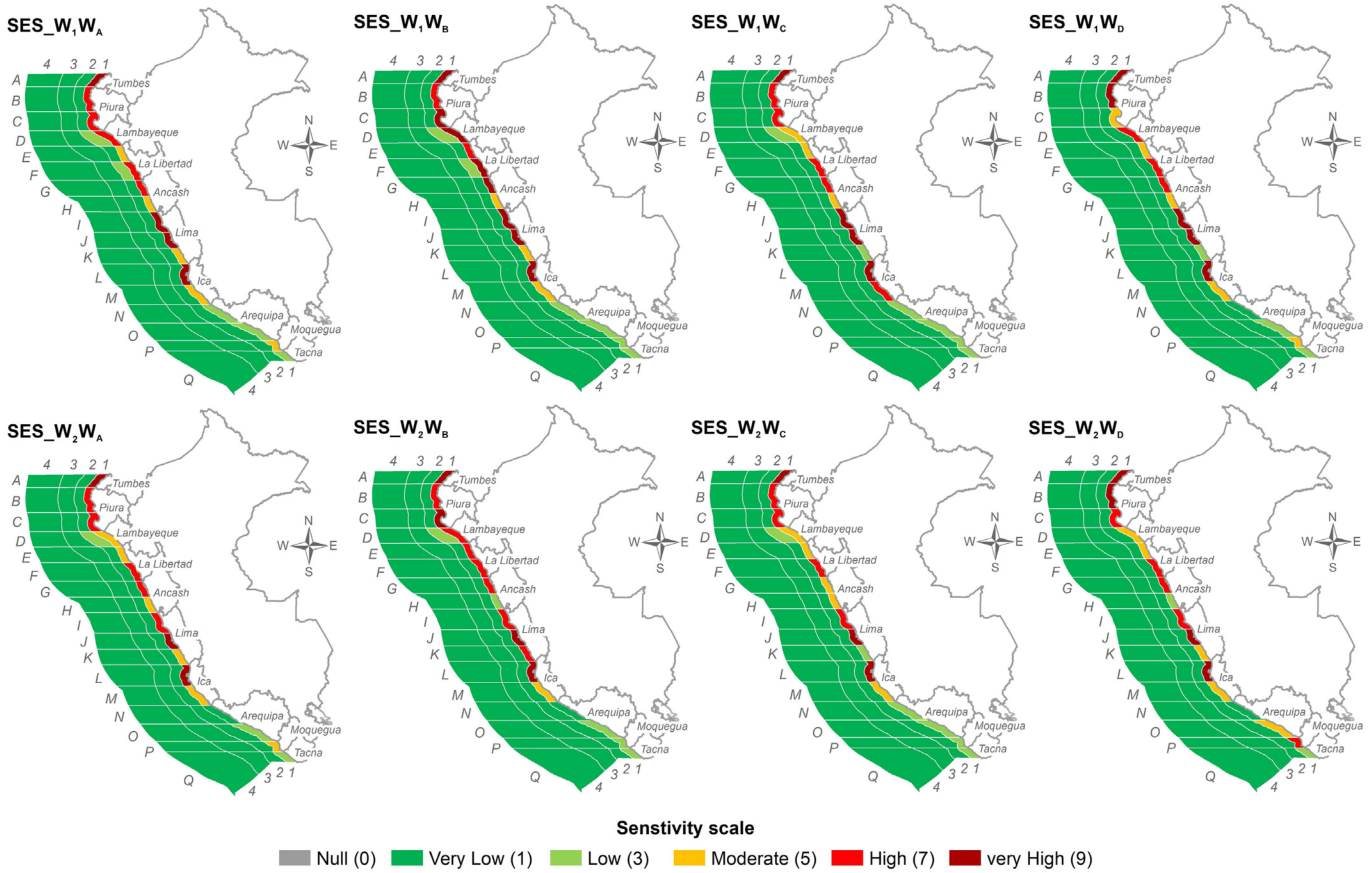

Fig. 5. Normalized results of the SES per weighting scenario: equal (W_1) and different (W_2) weights assigned to sensitivity indicators within their corresponding environmental component; equal (W_A) and different (W_B, W_C, W_D) weights assigned to the strategic physical, biological, and socioeconomic sensitivities (SPS, SBS, and SSS, respectively).

should be understood as a relative sensitivity between sectors and not as a sensitivity given by national or international standardized absolute scales. Likewise, lower sensitivity levels do not mean the absence of highly sensitive features to oil spills in a sector, but a lower number of them when compared to other sectors based on the spatial and temporal scale of the assessment.

The SES methodology was applied at a national level considering the sectorization of the entire Peruvian marine-coastal zone at a region/province level with different distance ranges to the coastline. This political-administrative sectorization allows a better management of the SES results at a region level, instead of focusing solely on geographical features. Since the SES assessment was based on this spatial coverage, the use of a different geographical arrangement and scale are expected to change the SES results. In any case, the SES methodology can be adjusted to different spatial scales to meet the needs of the different government levels and oil-related companies and organizations.

3.2. Screening oil spill risk (R)

Of the 10 OSS modelled in sector A1 for January 2021, only six produced oil beaching events within the seven-day simulation period (OSS1, OSS2, OSS4, OSS5, OSS6, OSS7) (Fig. 7). Likewise, in OSS3, OSS8, OSS9, and OSS10, no oil beaching was observed at any time interval. No OSS caused oil strandings within the first 24 h. On the other hand, the maximum number of oil beaching events among the 11 simulations run per OSS was obtained in OSS7, with three events, followed by OSS1 and OSS3 with two. The remaining OSS only generated one beaching event.

Only ten oil spill simulations among the 110 run for January 2021 reached the shoreline of sector A1 (Fig. 8), indicating a very low screening oil spill hazard (H), with an averaged likelihood frequency of oil beaching events or probability of oil stranding below 0.1. By relating the very low screening oil spill hazard level (H) and the very high strategic environmental sensitivity level (SES), the screening oil spill risk level (R) found in the northern coastal sector A1 is moderate.

This screening oil spill risk assessment represents an applied example of what could be done using the SES results. As observed in this practical exercise of only one month analyzed (January 2021), sector A1 (Tumbes) is highly sensitive to oil spills; nevertheless, it holds a very low likelihood of oil reaching its shoreline despite the worst-case spill scenarios modelled for that month. As in this exercise, other highly sensitive sectors may not hold a high oil spill hazard, and therefore, may not be considered high-risk areas, vice versa, sectors with a very low SES may hold a very high oil spill hazard and increase their risk. Relating the SES levels with oil spill hazard levels can then support the identification of sectors with a high oil spill risk, which are, in fact, areas that should be prioritized for the preparedness and rapid response during the OSCP process. A more comprehensive risk assessment in the entire Peruvian marine-coastal zone is then deemed necessary for a more robust National OSCP.

Although other more comprehensive methodologies are available in the literature to determine the oil spill risk, the proposed methodology provides a straightforward example of the oil spill risk assessment in a sector, by considering oil beaching events, which represent the biggest threats to the sensitive features of the marine-coastal zone. Some improvements in the proposed risk methodology may include increasing the number of scenarios, release points, simulation lengths (i.e., more than a week for major oil spills) and temporal ranges of metocean conditions (i.e., more months and more years to analyze), and including other current and future oil-related activities (e.g., ports or the traffic of different type of vessels).

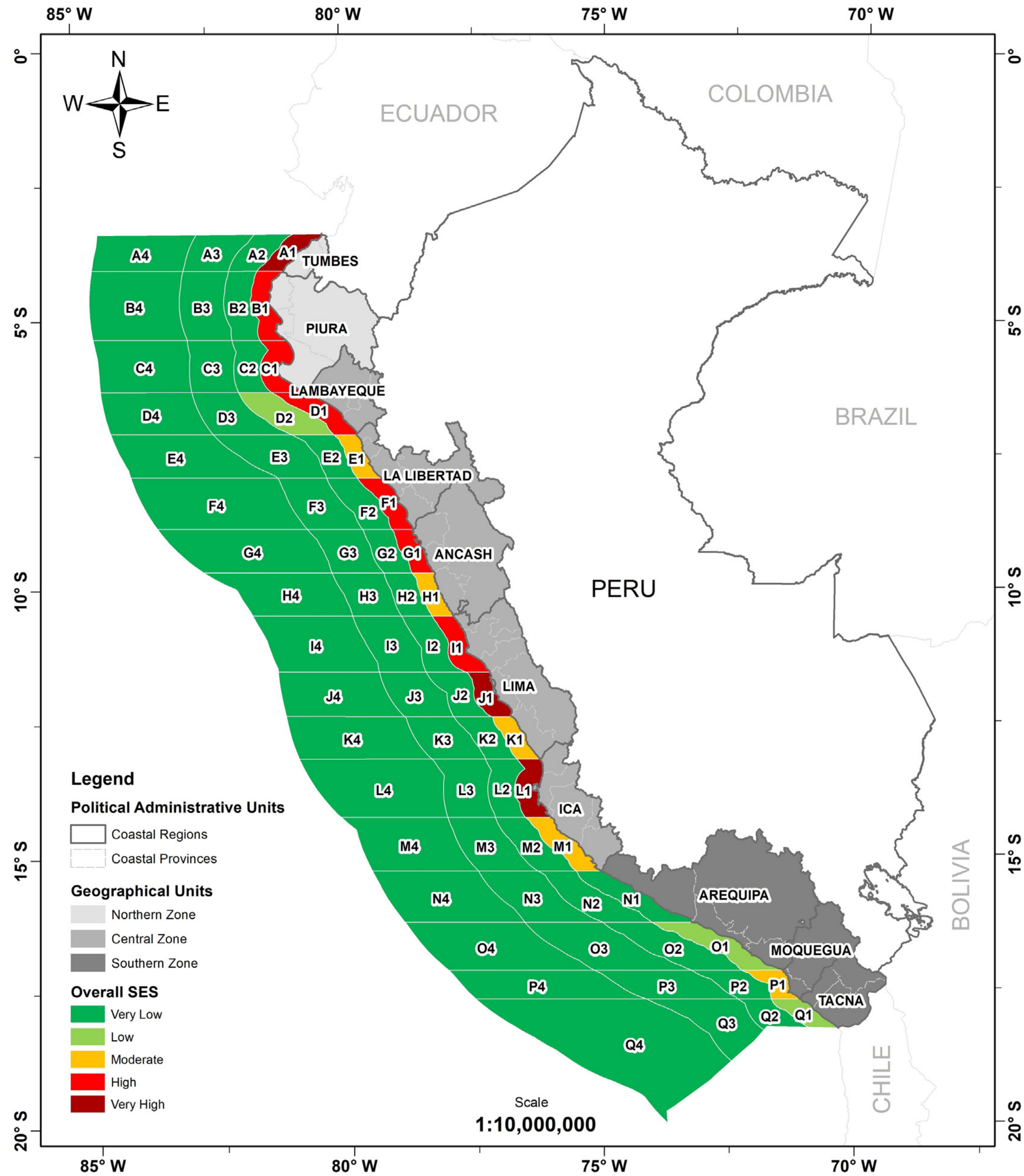

Fig. 6. Final SES of the 68 sectors of the Peruvian marine-coastal zone.

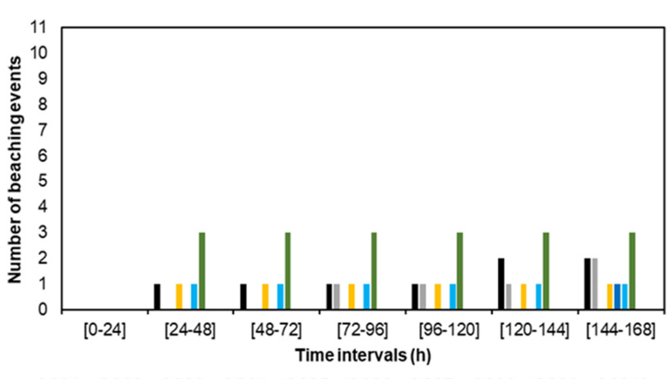

Fig. 7. Cumulative number of oil beaching events in sector A1 per time interval (every 24 h) for each OSS after the 11 simulations run for January 2021.

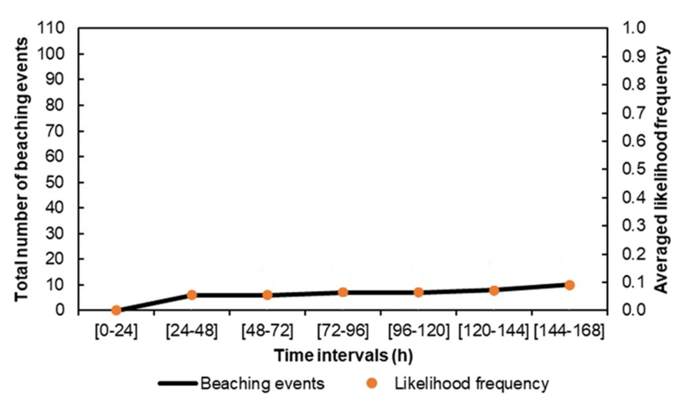

Fig. 8. Number of oil beaching events and averaged likelihood frequency of oil beaching per time interval in sector A1 (Tumbes) for January 2021.

4. Conclusion

The SES of the entire Peruvian marine-coastal zone was determined following a straightforward multicriteria methodology supported by an extensive physical, biological, and socioeconomic database, and key weighted sensitivity indicators framed under the Peruvian context. This decision-support tool—not available at a national level in the past—can be used in the OSCP by supporting the identification of high-risk areas which can lead to a better preparedness and rapid response to large-scale events. In addition, the SES results can support other relevant planning processes such as the integrated coastal zone management, the marine spatial planning, or the contingency planning of other liquid contaminants. The proposed methodologies are easily replicable in different ecological and socioeconomic contexts and geographical scales, given its low number of indicators and the simple inherent statistics applied which are enough to obtain quick and understandable managerial results for decision makers. Therefore, the different government levels and oil-related companies and organizations could adapt them to their most convenient geographical scale according to needs.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.158356.

CRediT authorship contribution statement

Pedro Walter Flores-Medina: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Visualization. **Antonio Augusto Sepp-Neves**: Conceptualization, Methodology, Software, Validation, Resources, Writing - Review & Editing, Supervision, Visualization. **Giovanni Coppini**: Conceptualization, Resources, Supervision. **Carmen Morales-Caselles**: Conceptualization, Writing - Review & Editing, Supervision, Visualization.

Declaration of competing interest

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

Acknowledgements

Thanks to the Eramus Mundus Joint Master's Degree on Water and Coastal Management (WACOMA) Consortium, namely the Universities of Cadiz (UCA), Bologna (UniBo), and Algarve (UAlg) for the technical support in the elaboration of this work. In addition, thanks to the Fondazione Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC Foundation) for the technical advice on oil spill modelling.

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