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Forecasting marine spill risk along the U.S. Pacific coasts

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ABSTRACT

This study analyzes historical trends and forecasts of spill risks in coastal counties along the U.S. Pacific, including Alaska and Hawaii. The method calculates spill impact, which rises with size but diminishes with age and distance from the coast. Over the past two decades, spill risks in California and Washington have increased significantly. Coastal counties in Puget Sound and San Francisco Bay have seen the highest increases, surpassing 2000 levels by 79 % and 39 %, respectively. Alaska experienced a moderate rise, while Oregon and Hawaii had smaller but noteworthy increases. Ocean currents may reduce risk by 38 % on average. Most counties are expected to experience increasing spill risks, particularly in Southern California and Southwest Washington, which could see nearly a 50 % increase by 2033 compared to present levels. These findings can help coastal zone monitoring and inform policies for protecting coastal regions, regulating marine transportation and reducing spill vulnerability.

1. Introduction

Marine spills, encompassing the release of crude oil, bunker, persistent and non-persistent fuel oil, chemicals, and other hazardous and noxious (HNS) substances into the marine environment, pose substantial risks and challenges worldwide. The occurrence of marine spills can be attributed to various factors, including accidents involving ships and offshore platforms, transportation of hazardous materials, industrial activities near coastlines, and natural disasters. These spills are a main component of ecological damage and their socioeconomic consequences can be severe, resulting in immediate and long-term impacts on marine life and coastal activities, such as tourism and fisheries, leading to significant economic losses. As a result, marine spills attract intense media attention and generate strong political debate about the appropriate actions to prevent them from happening and to counteract their environmental and socioeconomic impacts.

Alongside with this, during the last decades there has been a growing global interest in the study of the so-called blue economy aimed at preserving and managing marine assets with a view to fostering human progress and promoting sustainable growth. For instance, in the United States marine activities are of substantial importance to the economy and multiple policies underscore this significance as catalyst for growth and development; see, to name a few, DOA (1980) on Aquaculture, DOT (1999) on Maritime Transportation, NOC (2016) on Ocean Policies, NOAA (2018) on Coastal Tourism and Recreation, NOAA (2021) on Blue Economy Initiatives, DOE (2023) on Offshore Wind Strategies, and NOAA (2020) or NSF (2023) on Marine Research and Innovation Funding.

In reaction to these circumstances, a significant collection of enhancements in global policies, governmental rules, and even voluntary actions undertaken by oil and gas companies have arisen in recent times to mitigate marine spills worldwide. In the United States, several policies, regulations, and initiatives are in place to address this issue, such as the Oil Pollution Act of 1990 and its Marine Environmental Response Program (EPA, 1990), the National Contingency Plan established under the Clean Water Act (EPA, 1972), the Spill Prevention, Control, and Countermeasure Rule (EPA, 2023), as well as regulations for offshore activities from agencies such as the U.S. Bureaus of Safety and Environmental Enforcement and of Ocean Energy Management. Nevertheless, the outcomes of these efforts appear to have been mixed (Frynas, 2012; Frynas and Stephens, 2014; Berkowitz et al., 2016; Knudsen and Moon, 2021). Despite those measures leading to a reduction in the yearly average of such incidents, substantial marine spills continue to happen, affecting coastal regions in a non-uniform manner (NOAA, 2023a, 2023b; ITOPF, 2023).

Consequently, the design of these marine policies, regulations and initiatives needs some sort of monitoring of coastal vulnerability. Data availability allows a scientific approach, besides the political one, to be

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used in the management of the oceans and coastal areas (Barale, 2018). It is because of this that quantitative information is required, in particular, on the relative risks from marine spills involved in each coastal region. Assessing marine spill risks involves evaluating multiple interconnected factors. These include the volume and type of shipping and vessel activities in a given area, the surrounding environment, prevailing oceanographic conditions, *etc.* In recent years, advances in remote sensing technologies, spill modeling, and risk assessment methodologies have significantly improved our ability to predict and manage marine spill risks. These tools help in identifying high-risk areas, simulating spill trajectories, estimating potential impacts, and guiding decision-making processes related to spill prevention, preparedness, and response.

A significant body of literature exists regarding the assessment and modeling of marine spills, providing illustrative instances of the prevailing techniques used in their evaluation. For example, Gasparotti (2010) and Suter (2016) provide good manuals on the steps of risk assessment methodology and its importance for risk management. More specifically, Stewart and Leschine (1986) examines characteristic instances of various assessments related to the risk of marine spills, specifically focusing on choices made regarding input variables across diverse models. Grigalunas et al. (1988) present a model that uses an integrated ocean systems/economic approach to simulate the ecological and economic consequences of a spill, and gauge the subsequent financial losses incurred. Vanem et al. (2008) integrate the expenses linked to shipping incidents into a cost model, while also surveying earlier research on the financial implications of marine spills. Dalton and Jin (2010) explores the dimensions, occurrence rate, and cumulative volume of vessel-originated oil spills within marine protected zones in the United States. WSP Canada Inc. (2014) addresses marine spill scenarios within Canadian waters, employing a transportation model optimized for extensive geographical regions that combines factors such as spill composition and magnitude with oceanic conditions.

More recently, to name but a few, Shami et al. (2017) provides a risk assessment of oil spills where oil spill risk is quantified as a function of oiling susceptibility, concentration, frequency, and beaching time; Fernández-Macho (2016, 2017) proposes a metric based on spill size, distance from shore and prevailing sea currents, and constructs a marine-spill risk index to compare and rank the relative vulnerability of coastal regions in European waters; Guo et al. (2019) quantifies oil spill risk as a function of hazard frequency, vulnerability, and consequence; Neves et al. (2020) provides an overview of the oil spill risk analysis (OSRA) model for environmental impact assessment; Villalonga et al. (2020) presents an environmental management system for analyzing oil spill risk using probabilistic simulations; Nelson and Grubesic (2021) simulates oil spills at different times and locations in the Gulf of Mexico and ranks their severity using TOPSIS method; Brude et al. (2021) discusses a model for near real-time environmental calculation of oil spill risk; Dong et al. (2022) analyzed over half a million satellite images to create the first global map of oil slicks on the ocean, distinguishing between natural seeps and human-related sources such as oil platforms and pipelines; and Wang et al. (2023) presents a comprehensive framework for analyzing a marine oil spill risk using GIS and the entropy weight method.

In comparison, the current study employs a measure based on spill size, distance from shore, spilled substance and prevailing sea currents to assess the relative risk posed by marine spills along the Pacific shorelines of the United States based on data recorded during a historical period and extends the methodology for prediction purposes. The outcome is a marine spill risk index that makes it possible to rank these coastal regions, both at the end of the data collection period and at the conclusion of the forecast timeframe.

The paper's structure is as follows. Section 2 explains the method for the construction of the proposed marine spill risk index. Section 3 describes the marine spills data and the geographical framework used in this study, and Section 4 exemplifies the method with a study case. The results at the end of the sample period for the five U.S. states within the target area, along with their respective counties, are presented in Section 5, while Section 6 examines the index evolution and forecasts, and Section 7 analyses the effect of sea currents on the spill risk scores obtained. Finally, Section 8 summarizes the main conclusions.

2. Methodology

To assess the potential risk of marine spills in specific coastal areas, five main factors will be taken into account. Initially, spill characteristics such as (a) the extent of the spill originating from the incident, and (b) the distance between the coastline and the location of the incident, and (c) the characteristics, such as specific gravity and viscosity, of the spilled substance. Subsequently, geographical attributes will be evaluated, including (d) the influence of time and ocean currents during the incident's occurrence and location, and (e) the configuration of the targeted coastal zone.

To begin with, let us denote

$$I_{ik} = \frac{1 + (I_0 - 1)e^{S_0 - S_i^*}}{1 + D_{ik}} \tag{1}$$

as the impact exerted by spill i on the coastline of region k. Here, D_{ik} stands for the minimal distance between the spill's location and the coastline, $S_i^* = w_i S_i / g_i$ represents the magnitude of the i-th spill weighted by a damping factor so as to give more importance to the most current observations,[1] with S_0 as the smallest spill amount recorded or presumed in the absence of data, g_i is the specific gravity of the spilled substance, and I_0 is the minimum value that the impact would attain if the spill occurred precisely at the shoreline (*i.e.*, $D_{ik} = 0$). Hence, the calculated impact increases with the size of the spill but varies inversely with distance, and eventually with its age, from the coast in the interval $[0, 1)$, which has a more intuitive meaning and better mathematical handling than the previous formulation in Fernández-Macho (2016).[2]

The proposed method incorporates additional factors into the resulting algorithm —namely, coast lengths, substance characteristics and ocean currents— in a process that, in simple terms, can be explained as follows.

Step 1: Imagine there is a spill in the ocean. To estimate its potential reach simulating the action of time or, *i.e.* the "age" of the spill, without the influence of currents, we create q circular spread areas around the spill site. These circles have different sizes based on how big the spill is. More precisely, let $I(s) = s/q$, $s = q, q-1, \ldots, 1$, be the spill impacts considered from highest to lowest. For each of them, Eq. (1) can be used to establish the maximum distance $D_i(s)$ reached by a spill with impact $I(s)$ in the absence of sea currents. That is, the radius of the circle within which spill i generates an impact $I(s)$ is obtained as

$$D_i(s) = \frac{(1 - I(s)) - (1 - I_0)e^{S_0 - S_i^*}}{I(s)} \geq 0. \tag{2}$$

Step 2: Now, let's take into account the ocean currents. We use a simple short-range transport model to see how these currents could change the edges of the circles. This helps us adjust the boundaries of the spill's possible impact. In other words, let $C_i[x, y](s)$ be the circle centered at spill i of radius $D_i(s)$. Then

[1] A day-to-day exponential damping parameter was chosen so that older spills would have roughly 10 % less impact per year.

[2] In the scenario of a marine spill just on the coastline of region k distance would be $D_{ik} = 0$, resulting in an impact $I_{ik} = 1 + (I_0 - 1)e^{S_0 - S_i^*}$, so that $S_i^* \to S_0 \Rightarrow I_{ik} \to I_0$ and $S_i^* \to \infty \Rightarrow I_{ik} \to 1$. Values of $I_{ik} < I_0$ would occur when the spill is small (close to S_0) and some distance from the coast $D_{ik} > 0$. Besides, a default choice for I_0 can be deduced from the impact function as $1 - e^{-S_0}$, but in the algorithm the analyst is given a choice to increase/decrease the apportioned impact range for spills near the coast.

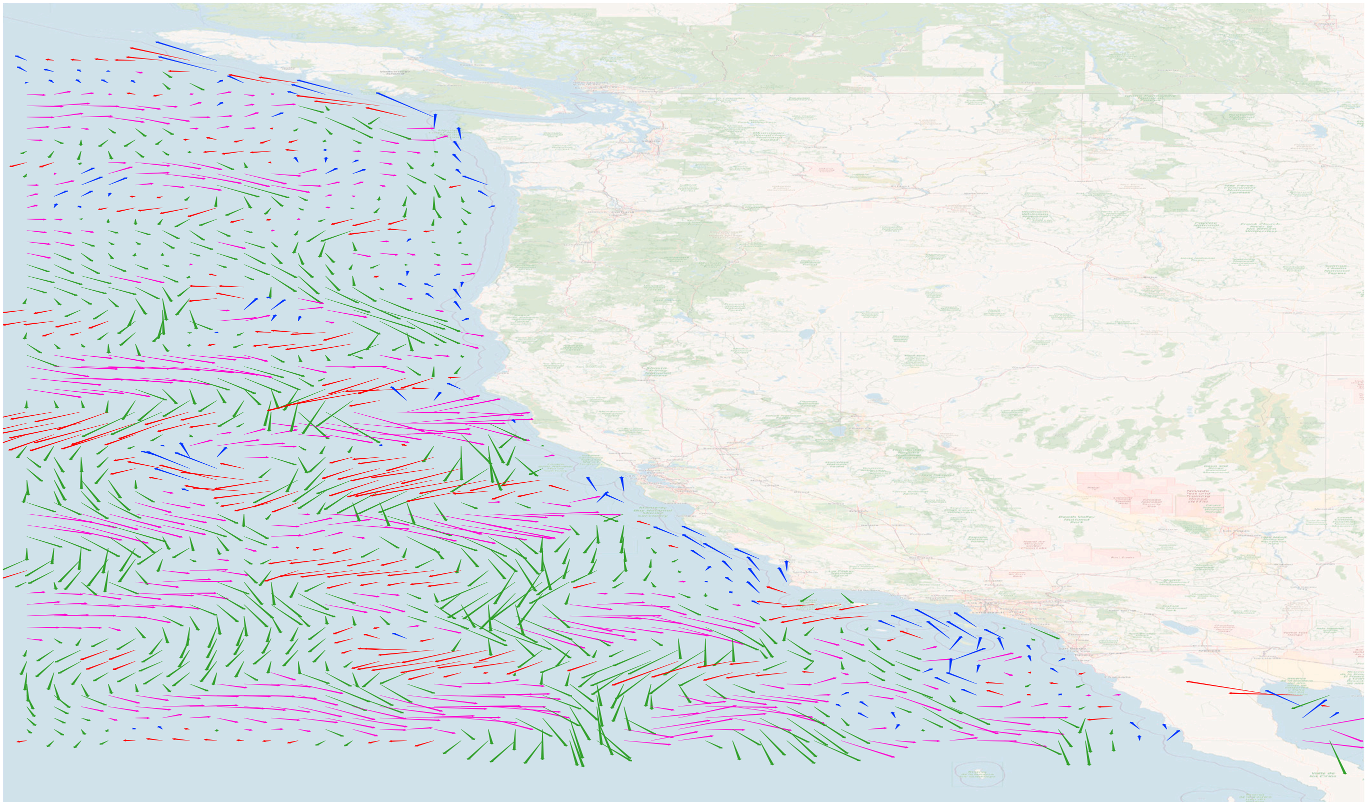


Fig. 1. NE Pacific currents' average current speed and direction at U.S. latitudes during year 2022.
Arrow length is proportional to (u, v) speed in m/s. Predominant direction of flow: eastward = magenta, northward = blue, westward = red, southward = green.

$$P_i[x,y](s) = C_i[x,y](s) + [C_i[x](s)\cdot u_i(x,y), C_i[y](s)\cdot v_i(x,y)] \quad (3)$$

defines the marine polygonal zone obtained by pushing $C_i[x,y](s)$ depending on the prevalent sea currents in that zone, where u_i, v_i are, respectively, the zonal (W-E) and meridional (N-S) average velocities of the sea current at each coordinate $[x,y]$ in which the incidental spill i occurred[3]; see Fig. 1.

Step 3: Next, we figure out how much of the coastline is affected by the spill at different spread sizes. Thus, for each coastal area k, let L_k^C be its total coastline length and let $L_{ik}(s)$ be the coastline length that lies within the range of spill i for the spread level s, *i.e.* the intersection of the spill affected zone $P_i(s)$ with the coastline of the target area k.[4] Then, this will be weighted by a sigmoid function v_i of the viscosity of the substance to take into account varying degrees of affectability and need for subsequent remediation. Therefore, the relative risk that the target coastal area k suffers from the marine spill i evaluated at the different spread levels considered is given by

$$R_{ik} = \sum_{s=1}^{q} \frac{(L_{ik}(s) - L_{ik}(s-1))\, v_i}{L_k^C} I(s), \quad \text{with}\, L_{ik}(0) = 0. \quad (4)$$

Step 4: Finally, each specific area k gets a score in the marine spill risk index that is calculated by adding up the risk values from all the different spills

$$R_k = \sum_{i=1}^{n} R_{ik}. \quad (5)$$

To ease comparisons, these scores can be scaled (usually between 0 and 10) for presentation purposes.

3. The data

The paper uses the statistical information and approximate geographic coordinates available in NOAA (2023b) database[5] for the 911 spill incidents near or on the U.S. Pacific coasts between 1969 and July 2023; (the red dots in Fig. 3 show the spill locations). During this period, the main cause of the largest spills (> 90,000 gallons) were groundings (15.4 %), while other important causes were fires or explosions (8.5 %), going adrift and sinking (1.7 %), collisions (1.3 %), pipeline ruptures (0.9 %), and hull failures (0.2 %). In many of those incidents the substance spilled being crude and heavy fuel oils, which cause severe impacts on the coastal environment and marine life and have a very difficult and expensive cleanup (Safe Harbor, 2019; NOAA, 2023c).

The geographical framework used in this paper focuses on the 69 counties commonly seen as constituting coastal Alaska, Washington, Oregon, California and Hawaii.

[3] Eastward and northward sea water velocities with Ekman and buoyancy components added obtained from the Ocean Surface Current Analyses (OSCAR) Project (Earth Space Research, 2023).

[4] The Open Source Geometry Engine was employed to create the necessary geographical shapes and for other tasks related to Geographic Information Systems (GIS).

[5] NOAA maintains a GIS database of, at the time of writing, more than 4400 incidents from tankers, carriers, barges and pipelines since 1957. About 1100 of those are spills on some of the west coast states (whether marine or not), and 911 are actual marine spills on the U.S. Pacific coasts with recorded spill greater than zero. The main information included are the date and geolocation of the spill, the type of substance and amount spilled, and the cause and description of the incident.

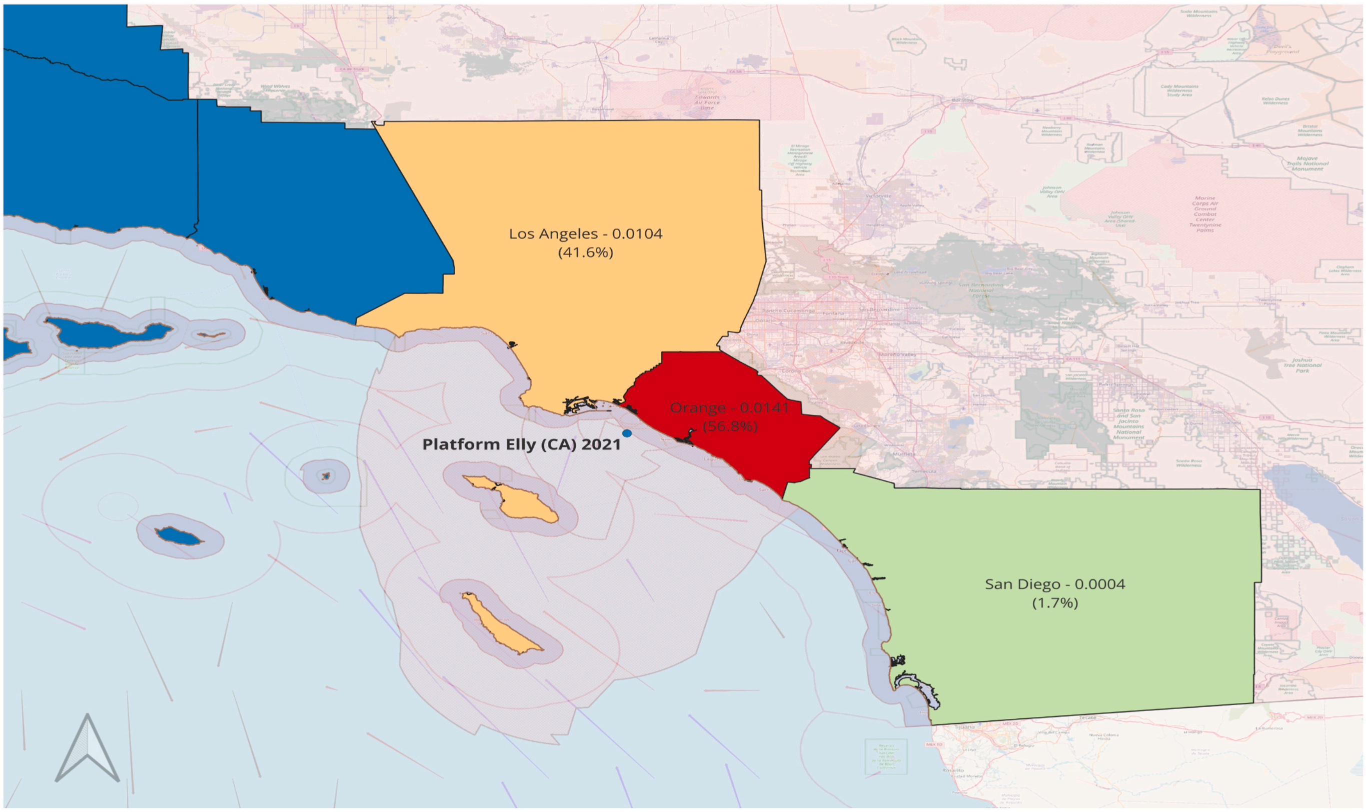


Fig. 2. Platform Elly pipeline spill - Huntington Beach (CA), 2021.

4. Case study: The 2021 California's Elly platform oil spill

As an example of the contribution of a spill to the risk index scores of neighboring counties, let us consider an incident *i* like that occurred on October 2nd, 2021 off the coast of California near Huntington Beach with average currents speed and direction for that year. According to NOAA records (NOAA, 2023b, $id = 10361$), around 0840 am that day "*USCG Sector Los Angeles/Long Beach contacted their NOAA SSC regarding a spill report. NRC Report #1318437 described an unknown sheen in the water at 1813 h local time on 01-OCT. Roughly 45 minutes later, a SENTINEL 1-A satellite image was obtained that became the basis for a NESDIS Marine Pollution Surveillance Report (MPSR) issued at 0015 h local (0815 UTC) on 02-OCT.*" NOAA estimates that about 25,000 gal of crude oil were spilled in that incident.

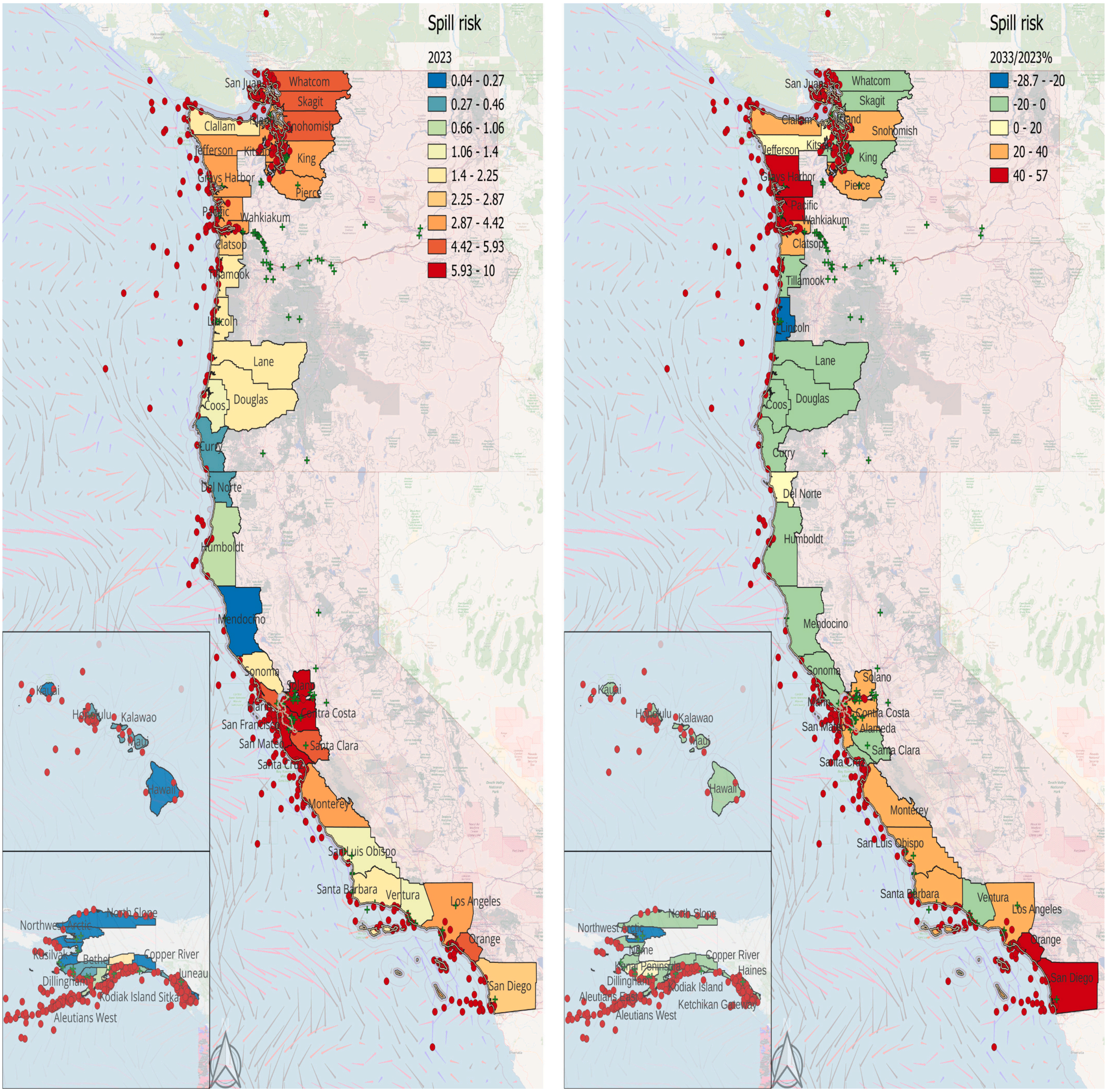
We use the proposed method with impact levels corresponding to five concentric spread zones $C_i(s)$ around the spill with radii $D_i(5) = 1.62, D_i(4) = 4.05, D_i(3) = 8.1, D_i(2) = 16.2$, and $D_i(1) = 40.5$ nautical miles respectively. From these values, the method uses the velocities of ocean currents at that point to simulate the five spread zones covered by the spill. For example, for the circular zone $C_i(4)$ around the spill, the coordinates at the four main cardinal points (in meters, from the NAD83/California Albers projected coordinate system), the average sea current velocities u, v at each point (in m/s, from the OSCAR project), and the resulting projected coordinates of zone $P_i(4)$ are as follows:

	$C_i(4)$		currents velocity		$P_i(4)$	
	x	y	$u(x, y)$	$v(x, y)$	x	y
East	210,552	−467,979	0.01521876	−0.02784169	213,757	−454,950
South	168,567	−506,101	0.01013796	0.04548056	170,276	−529,119
West	147,997	−479,549	−0.00861106	0.01282177	146,723	−485,698
North	179,548	−436,940	0.001426266	−0.01415206	179,804	−430,757

Then, the simulated currents-deformed spill areas $P_i(s)$ intersect with California coast affecting the three nearest counties in the following percentages of their total coastline length,[6]

S	$I(S)$	$L_{i,\text{LA}(06037)}(S)$	$L_{i,\text{Orange}(06059)}(S)$	$L_{i,\text{San Diego}\ (06073)}(S)$
1	0.856	0 %	5.48 %	0 %
2	0.713	1.12 %	11.76 %	0 %
3	0.57	2.44 %	4.17 %	0 %
4	0.428	6.42 %	16.93 %	0 %
5	0.285	86.03 %	61.67 %	4.13 %
		96.01 %	100 %	4.13 %

[6] As calculated by the Geometry Engine Open Source through R library rgeos interface.



(a) 2023 (b) 2033/2023%

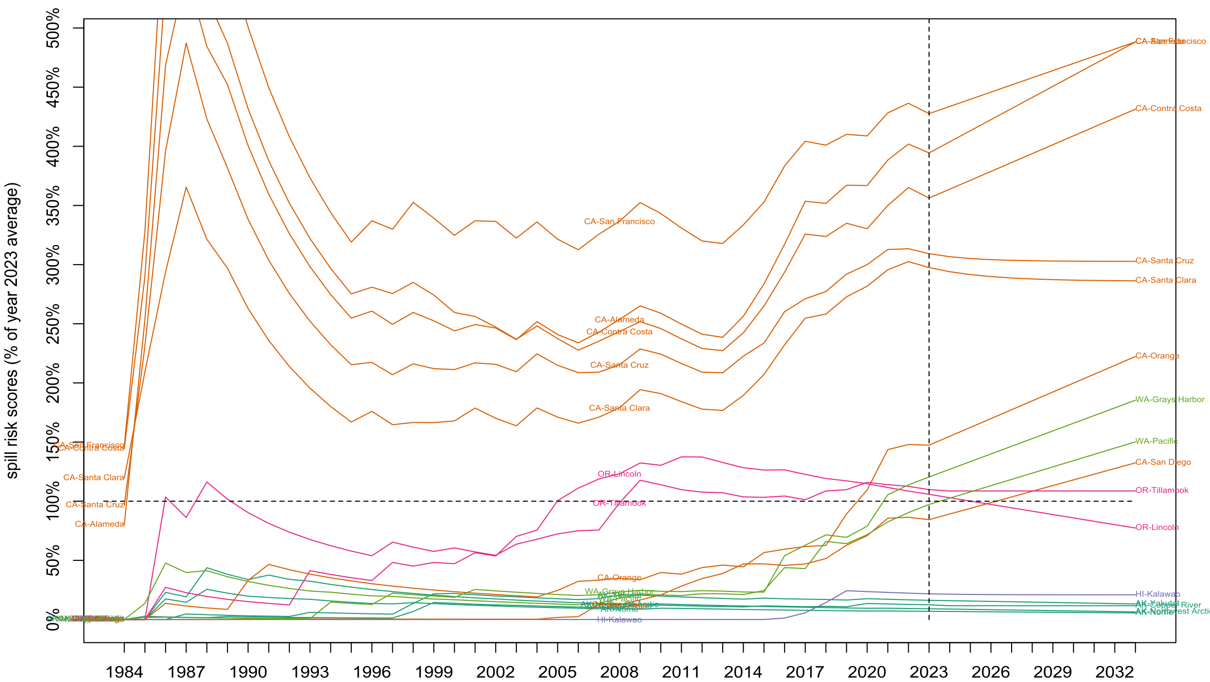
Fig. 3. U.S. Pacific coasts: spill risk index maps.

Finally, weighting the affected coastline by the corresponding impact levels $I(s)\nu_i$, the NOAA spill with $id = 10361$ contributes 0.5 % to the spill risk index scores of the coast of California in Table A.1, distributed as follows: $R_{i,\text{LA}(06037)} = 41.6\%$, $R_{i,\text{Orange}(06059)} = 56.8\%$, $R_{i,\text{SanDiego}(06073)} = 1.7\%$. Fig. 2 shows the potential geographic distribution of this spill's impact.

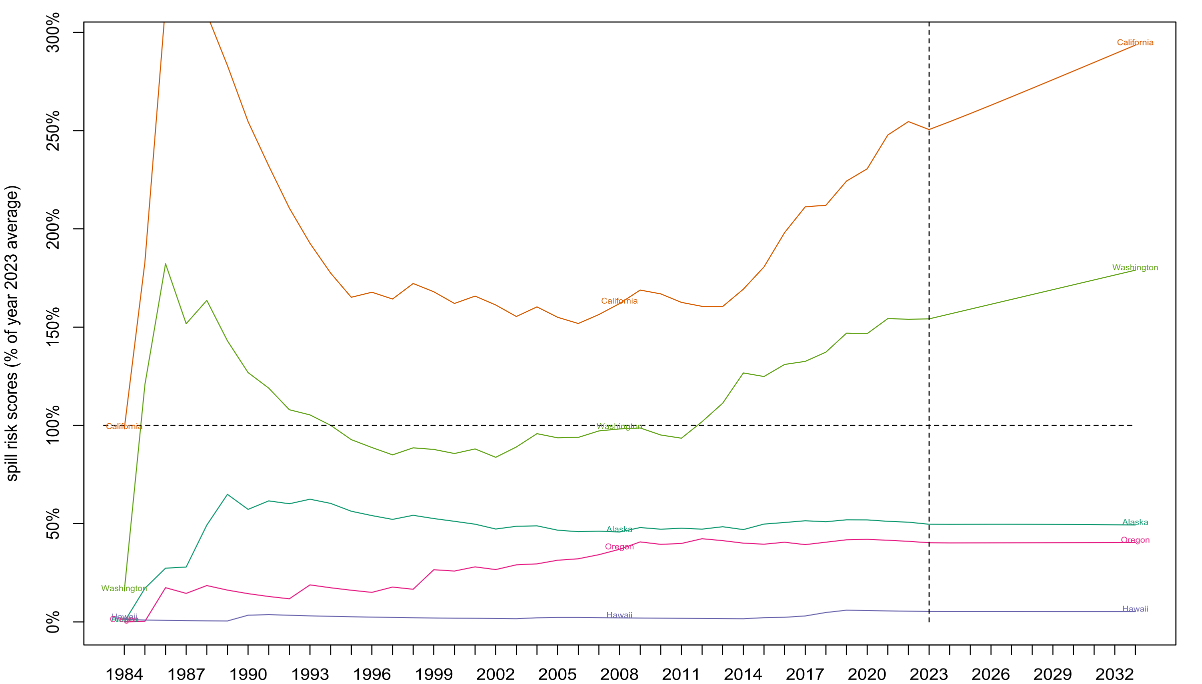
5. Spill risk index

The map in Fig. 3a shows the extent of the spill affected zones $P_i(s)$ for different spread levels of decreasing magnitude estimated for each of the incidents i from 1969 through July 2023. The map also shows the spill risk scores R_k obtained by each of the coastal counties in the U.S. Pacific coasts, according to the method described in Section 2; (the actual values for all counties considered can be seen in the Supplementary material, Table A.2). In the map, these counties are colored according to deciles of the index distribution, scaled from 0 to 10, using a blue-red gradient palette.

According to this ranking it can be observed that the coastal counties in California's San Francisco Bay and Washington's Puget Sound (Island, Kitsap, Snohomish, …) are subjected to the highest marine spill risk levels in the U.S. Pacific coasts. For example, seven counties in California obtain the highest scores in the index, with San Francisco, Alameda and Contra Costa scoring spill risks greater that 7 (over 10). In Washington State, Skagit, Whatcom and Island have scores above 5. On the other hand, Northern California, Southern Oregon, Hawaii and most



(a) Counties (selection; see Table A.2)



(b) States

Fig. 4. U.S. Pacific coasts: spill risk scores evolution and forecasts (1984 through 2033).

counties in Alaska, appear to be relatively free from spill risks, achieving the smallest scores, in all cases not much greater than 1.

6. Spill risk evolution over time and forecasts

To recall, the previous section used the method described in Section 2 to obtain spill risk scores by each county in the U.S. Pacific coasts using all available data in the NOAA database up to the current end of records in July 2023. But, in fact, the same exercise can be carried out for past years to obtain a multivariate time series, $R_k(t),\ t = 1969, 1969 + 1, \ldots,$ representing the evolution of spill risk scores by county. The values obtained are presented in the Supplementary material, Table A.1, while Fig. 4 shows the time series' evolution since 1984.

In general, we can appreciate very high spill risks during the 1980s, especially in California and Washington coastal counties. This situation began to be corrected in the 1990s, probably because of the introduction of spill response legislation and contingency measures such as the EPA (1990) after the Exxon Valdez disaster, reaching much smaller scores by the turn of the century. However, the last two decades have seen that trend reversed, and since 2000 the coasts of these states have witnessed

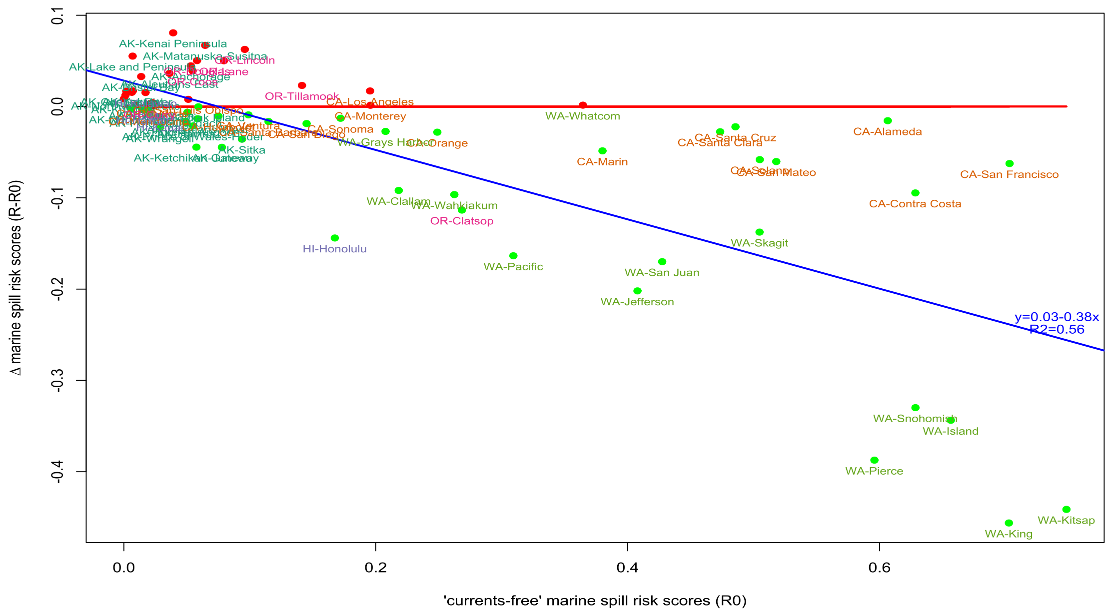


Fig. 5. U.S. Pacific coasts: effect of sea currents on marine spill risk index.
The blue line show the linear regression in 2023 ($\Delta R_i = 0.03 - 0.38 R_{0i}$). The F-statistic of the null of no currents' effect ($H_0 : b_0 = b_1 = 0$) is $F_{(2,67)} = 56.3$, which gives practically a zero p-value so that the hypothesis that sea currents have no effect on the spill risk scores is clearly rejected.

a remarkable increase in spill risk. In particular, the counties in San Francisco Bay and Washington's Puget Sound are now leading the U.S. Pacific risk league, surpassing their 2000's levels by 79 % and 39 % respectively.

Overall, the present scores in California and Washington reach on average more than 61 % above their values of year 2000 (CA: ×1.5, WA: ×1.8). On the other hand, Alaska has experienced a moderate rise since (×0.97), while Oregon and Hawaii's scores have undergone remarkable rises (OR: ×1.6, HI: ×2.8), albeit on comparatively smaller scales.

Once we have the evolution of spill risks over time, standard time series methods can be applied to extrapolate the risk scores into the future. In particular, we use the algorithm in Hyndman and Khandakar (2008) to automatically fit the best ARIMA model to the time series of each of the U.S. Pacific coastal counties in turn, and produce the corresponding predicted risk scores $R_k(t)$ during the forecast period $t = 2023 + 1 \ldots 2033$. The right end of the plots in Fig. 4 show these future trends, while the map in Fig. 3b shows the predicted percent change in spill risk for the coastal counties in the U.S. Pacific coasts; see the actual values in the Supplementary material, Tables A.1 and A.2b.

As can be seen, most of the counties appear to show a future uptrend in spill risk. This is especially true in Southern California and Southwest Washington, whose respective average spill risks may increase in almost 50 % during the forecast period, thus multiplying their 2000's levels more than eight and five times respectively. In comparison, Puget Sound and San Francisco Bay, which are at the forefront of the U.S. Pacific risk league, surpass those levels by just 74% on average.

On the other hand, many other counties show practically no variation in their predicted spill risks, with Santa Clara and Santa Cruz (CA), followed by Pierce (WA) and Lincoln (OR), showing some slight decrease as a reflection of their downtrends during the last few years of the recorded data.

At an aggregated level, the predicted spill risks reflect the recent upward trends. By 2033, California's spill risk is projected to rise by 17 % from current levels, multiplying its year 2000 levels by 1.8, so that it is expected to continue leading the spill risk league as it has been since spill incidents are recorded. Meanwhile, Washington State's overall risk score is expected to increase by 16 %, multiplying its 2000's levels by a slightly larger factor (×2.1).

7. Effect of currents

Ocean currents play an important role within the framework of a marine spill risk index, exerting either a beneficial effect by dispersing spills (resulting in lower risk scores), or a detrimental influence by pushing spills toward the coastline (leading to higher risk scores). As explained in Section 2, the calculation of the marine spill risk index scores R_k includes the effect of sea currents *via* the transformation of the original concentric zones $C_i(s)$ around the spill location into the final spill affected zones $P_i(s)$. However, if the risk scores were calculated from $C_i(s)$ directly, we would obtain 'currents-free' marine spill risk scores R_{0k}.

The scatter plot in Fig. 5 compare both measures for the coastal counties considered, showing the effect of ocean currents on their respective scores in July 2023. Those counties below the zero line (green dots), such as King County (WA), appear to experience a beneficial effect in the sense that their risk is diminished by the action of such currents in their waters. On the other hand, those territories above the zero line, such as Kenai Peninsula (AK), appear to have their risk increased by sea currents. Overall, there is a tendency of sea currents to have a beneficial effect rather than otherwise. This is reflected in the accompanying regression line, whose slope ($b_1 = -0.38$), given the relevant hypothesis test outcome, is significantly smaller than zero. Therefore, we may conclude that sea currents have a beneficial effect on spill risks in the sense that, on average, they may contribute a 38 % decrease in the risk scores. A similar exercise at the end of the forecast period, 2033, showed no major significant changes overall.

8. Conclusions

Marine spills have severe implications for both the environment and the economy of coastal regions. This paper introduces a metric that aims to measure, predict and compare the risk of marine spills in U.S. Pacific waters, which may serve as a tool for coastal monitoring and marine policies. In the study, the marine spill risk index assigns historical and future scores to each county in the U.S. Pacific coasts, enabling the assessment of its vulnerability to potential spills and facilitating comparisons with other coastal regions. By examining the spill risk of counties with high index scores, policymakers can gain insights for designing marine policies focused on monitoring coastal areas and mitigating the future impacts of marine spills.

The results of the study reveal the varying degrees of risk from marine spills among these coastal counties, highlighting significant heterogeneity. Certain counties, particularly those along Puget Sound and San Francisco Bay coasts, exhibit substantially higher marine spill risk compared to others. This outcome is unsurprising, considering the proximity of shipping routes to those coastal areas. In contrast, coastal counties in North California and South Oregon are relatively safer in terms of marine spill risk.

Additionally, the time trend of the index over the historical period plus the subsequent forecasts obtained enable us to evaluate the evolving vulnerabilities of each region. Thus, we see that California and Washington have witnessed remarkable increases in spill risks, with present scores reaching around 61 % above the levels of 23 years ago, while the rest have undergone substantial rises but on a much slower pace. As a consequence, by 2033 California's and Washington's risk scores are expected to increase substantially, by 17 % and 16 % respectively overall, which would continue to place California as the state with the highest spill risk since spill incidents are recorded, and Washington not far behind.

This study presents opportunities for further research. For example, although the proposed method has been kept simple to accommodate available data, it could be expanded by incorporating a more comprehensive transport-and-fate model. This enhanced model could consider additional factors beyond spilled substance characteristics and sea currents, such as spill source, weather conditions and more, contingent upon data availability. Initial tests, however, suggest that the index ranking remains relatively robust to these changes.

Another possibility for future development could involve exploring alternative data sources, such as the detailed inventories recently published by Dong et al. (2022), which could offer additional insights and perspectives, thereby further enriching our understanding of marine spill risks.

Moreover, the proposed method could be extended to forecast the future potential monetary losses associated with marine spill risk, connecting the index to a cost model that incorporates all relevant expenses resulting from a shipping incident. Recent large marine spills in the U.S. and elsewhere have focused attention on the potentially high cost of such events but little is known on the monetary cost supported by the respective coastal areas. In principle, the present marine spill risk index scores could be translated into a monetary value by first estimating a sort of dollar/risk score exchange rate (see *e.g.* Vanem et al., 2008; Yamada, 2009; Kontovas et al., 2010; Goerlandt and Montewka, 2015; Vidmar and Perkovič, 2023) and then multiply this exchange rate by the corresponding coastal region index scores. In a similar vein, one of the reviewers suggested incorporating future "demand for products" and "shipping traffic". Of course, if one could provide a scenario for future demand for oil&HNS-related products in the region under study or their future shipping traffic, that could be incorporated as exogenous factors into the forecasting algorithm for spill risk. It goes without saying that this opens the potential of comparison between different scenarios.

However, these extensions go beyond the scope of the current paper and warrant further research. Nevertheless, even without such refinements, the spill risk index can play a crucial role in the design of environmental policies by providing valuable information and insights into the vulnerability of coastal areas to marine spills. For example, the index could help policymakers to prioritize areas with higher scores, directing resources to where they are most needed, and to create tailored policies based on specific regional risks. Stricter regulations, improved monitoring, better emergency response, and sustainable practices can be implemented in high-risk regions, reducing spill occurrences. Finally, the risk index may foster awareness and a sense of responsibility among coastal communities, industries and environmental groups.

In summary, the paper's findings can help monitoring coastal zones and inform the development of policies aimed at safeguarding coastal areas, establishing marine transportation regulations, and reducing the vulnerability of sensitive resources to marine spills.

CRediT authorship contribution statement

Javier Fernández-Macho: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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