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Vulnerability in a Populated Coastal Zone and Its Influence by Oil Wells in Santa Elena, Ecuador

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Abstract: The oil industry requires studies of the possible impacts and risks that exploration, exploitation, and industrialization can cause to the environment and communities. The main objective of this study was to assess the vulnerability caused by oil wells of the Salinas and La Libertad cantons in Ecuador by proposing a multi-criteria spatial analysis methodology that would aid in land-use planning and management. The proposed methodology relates the variables of distance, identification of gas emission from oil wells, permeability, and the state of oil wells (DIPS). The methodology consists of: (i) the diagnosis of oilfield wells; (ii) environmental considerations of productive wells, wells in temporary abandonment, and wells in permanent abandonment; (iii) the vulnerability assessment of both intrinsic and extrinsic aspects of the wells; and (iv) the development of a vulnerability map and recommendations for land management. The results showed 462 wells in the study area, of which 92% were shown to be located in urban areas. Of the total, 114 wells were considered to be productive wells, 89% of which are in urban areas. The vulnerability map identified the areas to be addressed, which coincided with coastal and urban areas associated with oil production. Our main recommendation is to elaborate land-use planning regulations and build safety infrastructure around the wells to guarantee their distance from houses, beaches, and tourism-development sites. The vulnerability map was shown to serve as an essential diagnostic for decision making in managing oil territories, especially in coastal areas.

Keywords: vulnerability; oil wells; land-use planning; coastal area; sustainability

Citation: Herrera-Franco, G.; Montalván, F.J.; Velastegui-Montoya, A.; Caicedo-Potosí, J. Vulnerability in a Populated Coastal Zone and Its Influence by Oil Wells in Santa Elena, Ecuador. *Resources* **2022**, *11*, 70. https://doi.org/10.3390/resources11080070

Academic Editors: Katharina Gugerell, Gregory Poelzer and Andreas Endl

Received: 15 June 2022
Accepted: 21 July 2022
Published: 29 July 2022

1. Introduction

The oil and gas industry searches for hydrocarbon reservoirs for exploitation worldwide using prospecting techniques such as seismic exploration [1]. Once a reservoir has been identified, wells and surface facilities are designed to exploit the oilfield [2]. Hydrocarbons are transported through pipeline systems to refineries for conversion into fuels and feedstock for other industries [3,4]. Oil and gas are exploited in the open sea or sedimentary basins worldwide [5,6], but exploitation can also occur in and nearby urban areas [7,8]. Exploiting these energy resources is beneficial to humans' economic development and energy consumption [9,10]. However, exploitation can negatively impact society and the environment [11]. A common example is offshore oilfields, which can potentially spill oil into marine environments. Accordingly, researchers can use probability and simulation to prevent and respond to these events [12].

Vulnerability is defined as the susceptibility of a system to a specific hazard [13]. It can also be considered the risks a system faces when negatively affected by specific disturbances [14]. The term also refers to potential loss or damage at either the individual or societal level [15]. There are different vulnerability types: physical, social, economic, and environmental [16]. Therefore, vulnerability studies are important for identifying and assessing different levels of natural and industrial risks affecting people and the environment [17].

There are different methods to determine the different types of vulnerabilities. For example, the "Poverty Assessment Tools" method can be used to analyse poverty in socioeconomics [18] and the analysis of macroeconomic risks using financial indicators has been used in economics [19]. When it pertains to territories associated with industrial plants, the vulnerability index helps assess the probability of risks [20]. Landslide vulnerability assesses a potential damage index by relating physical and social vulnerability [21]. Other methods include seismic vulnerability assessments, which relate variables such as building materials, population, lithology, and faults to obtain a map of vulnerability to earthquakes in a region [22]. In the case of floods, a vulnerability index can be obtained by relating the variables of exposure, sensitivity and adaptive capacity [23]. In the case of fire, the authors of previous studies have analysed vulnerability with the fire risk index, which considers the ignition and evacuation phases [24]. In addition, vulnerability to noise can by assessed by measuring the noise level and the effect of exposure to such noise on people [25].

Quantitative studies on environmental vulnerability have considered indicators such as vegetation, soil, landscapes, and meteorological information and related them to the social economy to understand their socio-environmental impacts and aid decision making [26,27]. These studies have often used satellite images and mathematical models to generate environmental protection maps [28], e.g., mathematical vulnerability models allow for the analysis of environmental impacts in cities and their relationship to the health of their communities [29].

Urban areas are vulnerable to natural events and risks that are mainly generated by anthropogenic activities [30]. As a result, vulnerability studies have been used to detect hazards from natural events such as floods and earthquakes [22,31]. Climate change also generates vulnerability in coastal areas due to sea-level rise, losses of territory, tourism, and cyclones [32,33]. One example is the vulnerability of coastal aquifers' caused by seawater intrusion due to offshore oilfields' hydrocarbon exploitation [34]. The metals present in oil spills are toxic to the health of humans and animals alike because plants and humans absorb them through the food chain [35]. In addition, oilfield workers can suffer from fatigue, headaches, and high stress levels, among other symptoms [36].

The oil and gas industry can affect the environment and land use [37,38]. Of the methodologies used to assess vulnerability in a territory due to oil activities, some are focused on social, physical, environmental, and/or economic vulnerability; the coastal or inland environment; and quantitative and/or qualitative measures. For example, the authors of one study presented a model for assessing the economic vulnerability of oil-importing countries to high oil prices per barrel due to different geopolitical and climatic conditions [39]. Other models for assessing oil spill vulnerabilities consider environmental, social, and economic aspects explicitly designed for coastal environments [40–44] and sensitive areas such as forests [45]. Other models have been used to assess the vulnerability of groundwater to oil activities [46–48] and watersheds to fracking in mountainous areas [49]. In addition, the authors of previous studies developed vulnerability models for cognitive activity in children generated by the presence of petroleum products in the air [50]. There have also been cases where the vulnerability of different vertebrate species and seabirds to developing offshore platforms and oil spills was analysed [51–53].

Some models enable vulnerability assessments due to the presence of refineries in coastal areas where physical, social, and environmental aspects are considered [54,55]. The risk of gas pipelines to seismic events [56] and the vulnerability of these infrastructures to abiotic and biotic factors that cause corrosion have been analysed using probabilistic methods [57]. Risk analysis has been used to evaluate the vulnerability of different oil infrastructures to vandalism [58]. A more comprehensive comparison of methodologies can be found in Supplementary Materials Table S1.

Researchers often seek to reduce the vulnerability generated by the oil and gas industry to people and territories. For example, a study on the relationship between intensity and sensitivity was conducted in Hassi R'Mel, Algeria [59]. Other studies have focused on reducing vulnerability by reducing the area of operation of hydrocarbon activities in protected areas such as the Yasuní National Park in Ecuador [60]. In the Czech Republic, the Lbr-1 oilfield planned for CO_2 storage was assessed for risk and vulnerability under ISO 31000:2009 [61]. Other studies in Turkana, Kenya linked the interaction between oil exploration/exploitation, conflict, water, and climate change vulnerability to their communities. Small groups of people were surveyed, and these data were correlated with temperature and precipitation data [62,63]. In Brazil, probability and numerical simulation models were used to assess vulnerability to oil spills [45]. The authors of other studies on vulnerability to oil spills have used probability to determine the environmental sensitivity index [64]. Furthermore, socio-economic vulnerability due to extensive oil spills has been studied by relating the number of establishments to high, medium, and low proximities to oil spills and their levels of exposure [65].

In Santa Elena Province, Ecuador, the oil search and exploitation era began in 1911 with the drilling of the Ancon 1 well [66]. The population grew near the oil infrastructure during the time of peak hydrocarbon exploitation activities. In this context, our research question was: how should one develop a methodology to help measure a territory's vulnerability due to oil wells in populated areas? This work was aimed to propose a methodology based on the variables of distance (to populated areas and water bodies), identification of gas emission from oil wells, permeability of soil around oil wells, and state of oil wells (DIPS) to assess a territory's vulnerability to oil wells using technical and environmental analysis for area management. The proposed methodology was applied to a coastal area with oil activity that coexists with urban areas.

The methodology was conducted in three phases: reviewing bibliographic information, creating an inventory of wells, and assessing the conditions related to their geographical environments. The DIPS methodology was used to consider the key criteria of the territory associated with the influence of oil wells for subsequent application to the case study and to obtain vulnerability maps.

Study Area

The study area is located at the centre of the coast of Ecuador (Figure 1). The Ancon oilfield comprises a large part of the territory of Santa Elena Province (SEP). The territorial extension of the province is 3665 km^2 [67], of which 1200 km^2 correspond to the oilfield [68]. The cities of Santa Elena, La Libertad, and Salinas have a combined population of 401,178 inhabitants [69]. The main economic activities in the SEP are tourism, mining, oil production and refining, and fishing [70]. The parish of Ancon is a sector that belongs to the Decentralised Autonomous Government of Santa Elena. The cultural heritage Santa Elena in Ecuador is tied to its English architecture and the site of the country's first oil well [71].

The geological framework of SEP consists of soils and sedimentary rocks [72]. SEP is a coastal region of Ecuador with significant geological complexity [73–75], with stratigraphic successions and sequences ranging from the Upper Palaeocene to the subsidence of the Progreso Basin [76]. Figure 2 shows the formations present in this area, listed according to the following stratigraphic deposition: Ancon, Socorro, Passage Beds, Azúcar, Santa Elena, Cayo, Calentura and Piñón. The Calentura Formation has potential as a hydrocarbon-bearing rock, and the Socorro and Passage Bed formations are reservoir rocks [77]. The Cayo Formation outcrops on the offshore front present clayey and calcareous shales with secondary silicification. The Azúcar Formation has rocks of moderate tenacity, containing alternating thin sandstone layers and black siliceous shales. The Ancon Group has clay

Passage Bed, Socorro, and Seca formations. They have a sequence of greyish green clays, thin sandstone layers with greenish-grey shales, and sandstones with shales in thick layers, respectively [78]. The Tablazo Formation is the most outstanding in Santa Elena, and it presents fine agglomerates, sandstones, and fossiliferous sands [74] used for construction and handicraft materials. Finally, there are indications that the Ancon oilfield and the Peru-Bank block belong to the same petroleum system, the Progreso Basin, which is part of the Cretaceous–Paleogene [79]. Furthermore, the oil from the Ancon field has an API gravity of 33.4° [80], so it is the highest quality oil in Ecuador.

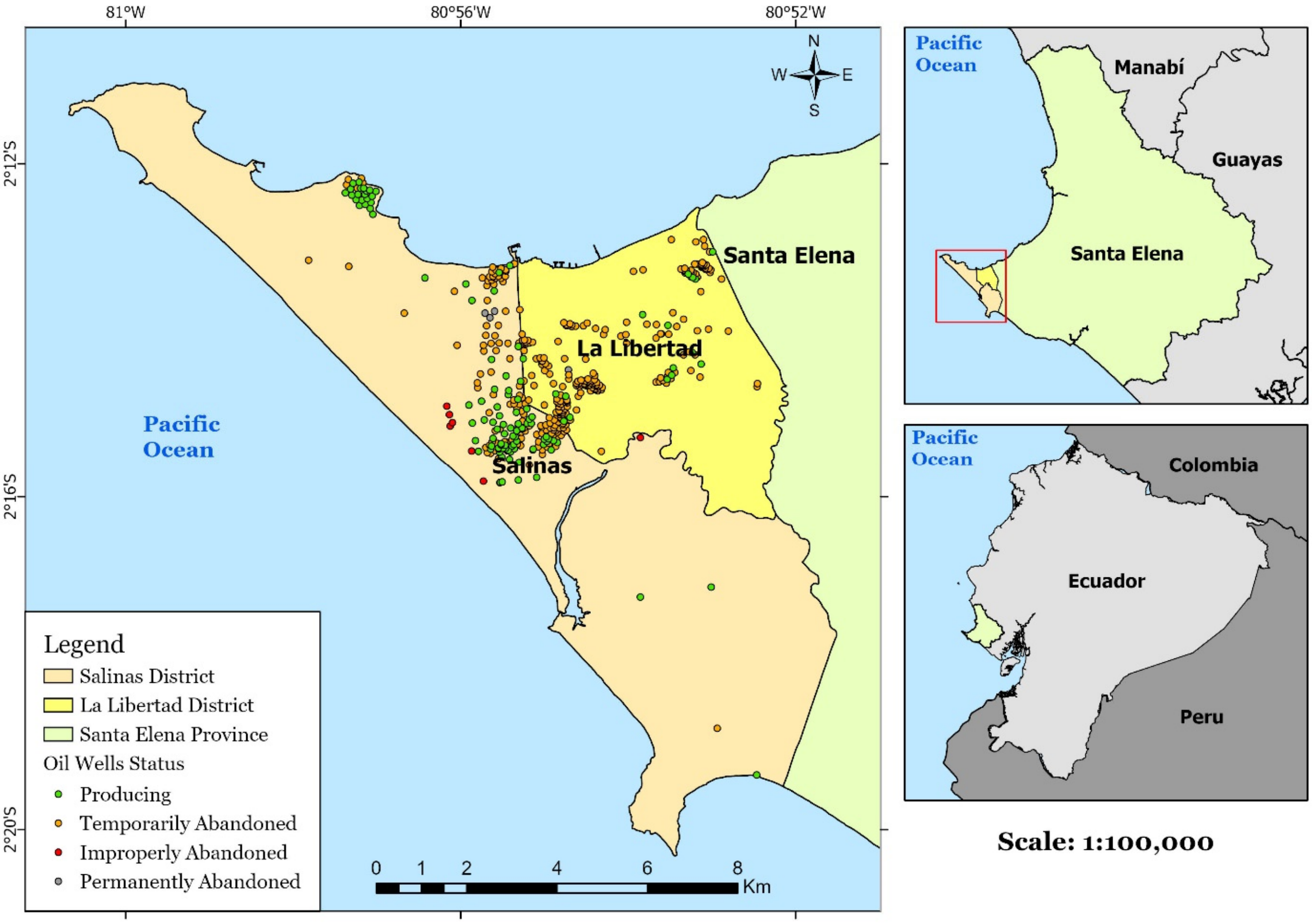

Figure 1. Location of the study area: productive, temporarily abandoned, improperly abandoned, and permanently abandoned wells.

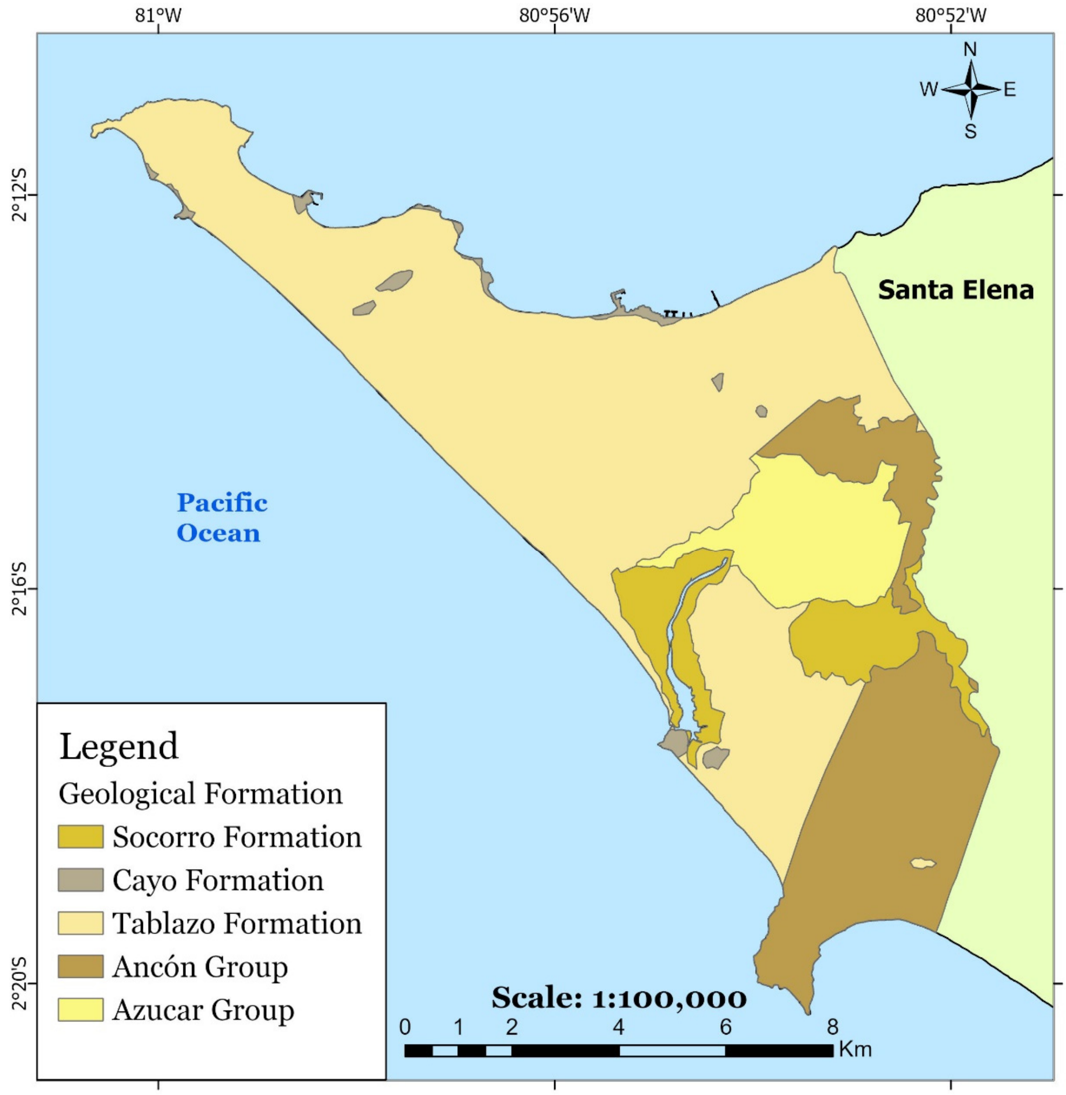

Figure 2. Geological formations in the study area.

2. Materials and Methods

The methodology of this study consisted of three phases (Figure 3): Phase 1 focused on reviewing scientific literature, determining vulnerability types, analysing the territory's current situation, and collecting available data (mainly regarding their geographical location) from oil wells [81,82].

Phase 2 covered the characterisation of the oil wells. First was the classification of oil wells into productive, temporarily abandoned, improperly abandoned, and permanently abandoned wells. Then, this DIPS methodology identified the proposed variables; information was collected in situ through focus groups and the Delphi method. The information was provided by the community and experts on the environment, territory losses, risks, and petroleum engineering [83,84].

Phase 3 was focused on applying the DIPS methodology, generating the vulnerability maps of the study area, and proposing strategies for decision making in territorial management.

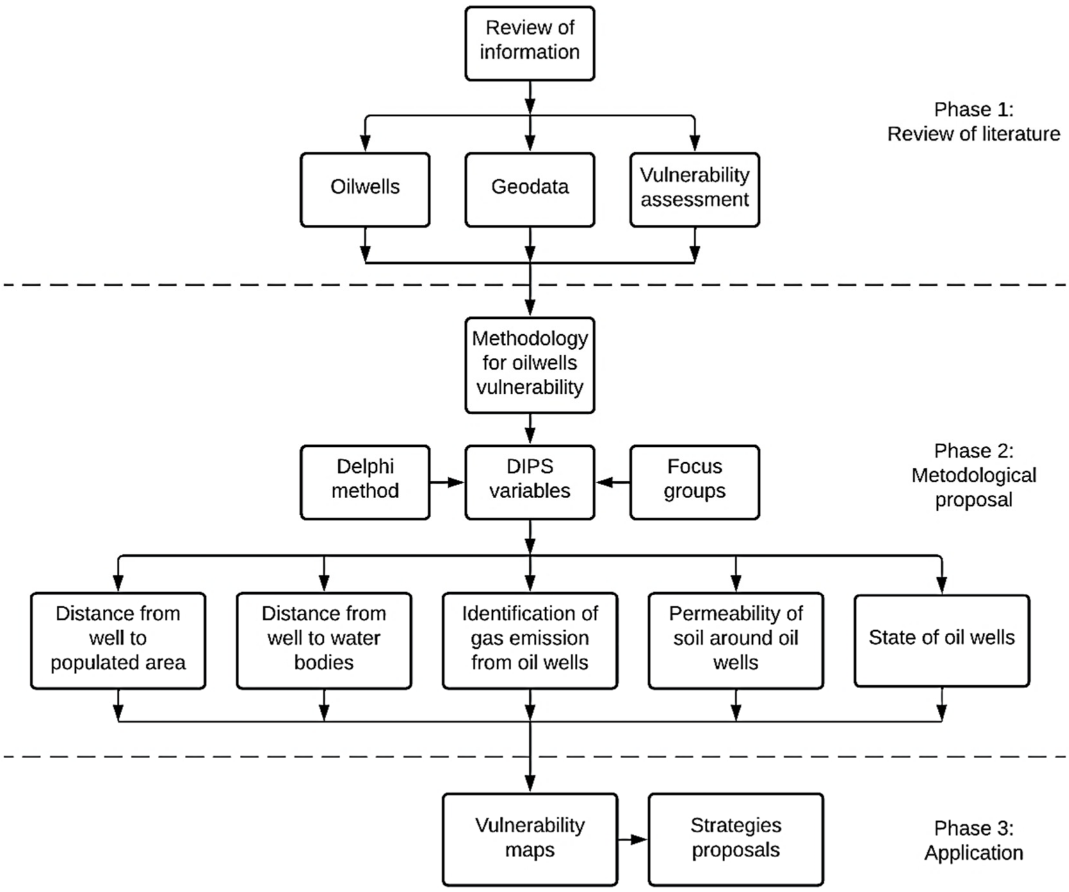

Figure 3. Diagram of the study method.

2.1. DIPS Methodology Proposal

The DIPS methodology is qualitative (involving the people in a study area) [85] and quantitative (because it measures and compares vulnerability) [86]. First, the DIPS variables were integrated into a geographic information system (GIS) to obtain a vulnerability map with discrete and continuous data using ArcGIS Pro 2.8.1 software, Environmental Systems Research Institute, Inc. (ESRI), Redlands, CA, United States [87]. Then, a weight and rating were assigned to each variable for the discrete data map.

2.2. DIPS Variables

2.2.1. Distance from Oil Wells to Populated Areas

This variable received the highest weighting, with a score of 5, because wells can spill hydrocarbons and emit or concentrate gases that can affect the nearby populations when exposed to certain pressure, temperature, and fluid volume [88,89]. In addition, to determine the populated areas, the "populated area" class was selected from the current land-cover and land-use data available in the governmental entity's geoportals [90].

Subsequently, the proximity of oil wells to urban areas was determined using different buffers in ArcGIS Pro. The methodology applied five buffer rings around the wells according to the environmental laws of local entities [91,92], which define the radius of influence of safety and affectation of the wells. The safety and buffer distances were defined by the variables x_1, x_2, x_3, x_4 and x_5 using the following expressions:

Equation (1): x_1 corresponds to the minimum distance variable r_{min}, with a rating of 5. It is suggested that this distance be greater than 10 m (m).

$$x_1 = r_{min}, \tag{1}$$

Equation (2): x_5 defines the largest buffer distance, r_{max}, which is considered safe and feasible for land use, thus earning a rating of 1.

$$x_5 = r_{max} \text{ to } 2(r_{max}) \quad (2)$$

Equation (3): d is the difference between the maximum and minimum distances divided by the ranges used in DIPS.

$$d = (x_1 - x_5)/5 \quad (3)$$

Equation (4): x_2 corresponds to the second rank, with a rating of 4.

$$x_2 = x_1 \text{ to } (x_1 + d) \quad (4)$$

Equation (5): x_3 corresponds to the mid-range, with a rating of 3.

$$x_3 = (x_1 + d) \text{ to } [(x_1 + d) + 2d] \quad (5)$$

Equation (6): x_4 is the penultimate rank, with a rating of 2.

$$x_4 = [(x_1 + d) + 2d] \text{ to } [(x_1 + d) + 4d] \quad (6)$$

2.2.2. Distance from Oil Wells to Water Bodies

Water bodies are in coastal and inland environments. In coastal environments, they are linked with the sea and sea mouths [93]. On the other hand, in inland environments, water is associated with lagoons and rivers [94]. The distance variable considers the distance of oil wells to different surface water bodies that could be contaminated by hydrocarbons, thus receiving a weight of 4. This distance was determined in ArcGIS Pro using three buffer rings: the first ring corresponded to the first 10 m, with a rating of 3; the second ring corresponded to a distance between 10 m and 30 m, with a rating of 2; the third ring corresponded to a distance between 30 m and 100 m, with a rating of 1; and the final ring corresponded to distances greater than 100 m, with a rating of 0.

2.2.3. Identification of Gas Emission from Oil Wells

Oil wells emit gas flows into the environment [95,96] that can be perceived by an area's inhabitants, causing health and environmental risks [97–99]. Accordingly, this variable received a weighting of 3. In order to determine the presence of gases, focus groups in the study area were asked to report the perception of gas odours in oil wells, assigning a rating of 2 where they were perceived; otherwise, the rating was 0. The gas perception data were georeferenced to nearby wells in ArcGIS Pro software.

2.2.4. Permeability of Soil around Oil Wells

Permeability is the ability of a medium to enable the flow of fluids from one point to another [100]. As a result, hydrocarbons can infiltrate the ground during the exploitation and permanent abandonment processes, affecting aquifers [101,102]. Therefore, this variable was given a weighting of 2. In this variable, the "permeability" class was selected from the hydrogeology data available in governmental entities' geoportals [103]. As a result, soils were classified as high permeability with a rating of 3, medium permeability with a rating of 2, and low permeability with a rating of 1 [104].

2.2.5. State of the Oil Wells

The state of an oil well defines its productive condition, being classified as productive, temporarily abandoned, improperly abandoned, and permanently abandoned wells [105,106]. This variable was assigned a weight of 1. Productive wells can generate some risk, so they received a rating of 3. Temporarily abandoned wells that can be productive were assigned a rating of 2. Improperly abandoned wells have no surrounding safety infrastructure and were thus assigned a rating of 1. Finally, permanently abandoned wells comply with environmental requirements to ensure safety in their surroundings, so they were assigned a rating of 0.

Table 1 shows the DIPS variables alongside their weight (ranging from 1 to 5, depending on the environmental impact) and rating.

Table 1. DIPS matrix for vulnerability generated by oil wells.

Variables	Rank	Rating	Weight
Distance from oil wells to populated areas (Dp)	$<x_1$ x_2 x_3 x_4 x_5	5 4 3 2 1	5
Distance from oil wells to water bodies (Dwb)	<10 10 to 30 30 to 100 >100	3 2 1 0	4
Identification of gas emission from oil wells (I)	Sometimes No	2 0	3
Permeability of soil around oil wells (P)	High Medium Low	3 2 1	2
State of the oil wells (S)	Producing wells Temporarily abandoned wells Improperly abandoned wells Permanently abandoned wells	3 2 1 0	1

The ratings and weights of the variables were multiplied together to obtain the DIPS variable score.

Equation (7) shows the product rating-weight score, where S is the score, R is the rating, and W is the weight.

$$S = R \times W \quad (7)$$

The total score (St) was calculated with the sum of the score in each variable, as indicated in Equation (8), adapted from the DRASTIC (depth–recharge rate–aquifer–soil–topography–zone's impact–hydraulic conductivity) method, and used to determine the vulnerability of aquifers [84]. The maximum St value was 52, resulting from the multiplication of the highest value in rating in the variable by its weight. The minimum value was 7, resulting from the multiplication of the value of the weight of each variable by the minimum value of its rating.

$$St = Dp_R \times D_W + Dwb_R \times Dwb_W + I_R \times I_W + P_R \times P_W + S_R \times S_W \quad (8)$$

The valorisation in this methodology was classified as high, medium, and low vulnerability, as shown in Table 2.

Table 2. Classifying vulnerability according to score.

Vulnerability	Score	Colour
High (H)	37–<52	Red
Medium (M)	22–<36	Yellow
Low (L)	7–<21	Green

Finally, all the data were integrated into ArcGIS Pro to generate the vulnerability map. As part of this integration process, it was necessary to convert all data to raster to assign the respective ratings and weights of the variables. In addition, a Kernel density analysis was carried out to create a raster of continuous data based on an oil well's status. Subsequently, the preliminary raster data were merged using the Raster Calculator tool, thus obtaining the vulnerability map of the region.

3. Results

Application of the DIPS Methodology

Salinas, located in the most outstanding area of continental Ecuador, is one of the most visited places in SEP due to its landscapes and beaches [107]. The local economy is based on fishing activity, handicrafts, and tourism [108]. In La Libertad, there is infrastructure for oil production, storage, and refinement. Salinas and La Libertad had estimated populations in 2020 of 94,590 and 117,767, respectively [69]. The study area has 462 oil wells, with 425 in populated areas, 101 productive wells, 320 temporarily abandoned wells, and 4 permanently abandoned wells. Outside the urban areas, there are only 13 productive wells, 17 temporarily abandoned wells, and 7 improperly abandoned wells. In Salinas and La Libertad, the safety or buffer distance from wells to civil infrastructure must be 30 m according to the law of ordinance that regulates land use and urban development in areas of hydrocarbon activity [91]. However, in other cities with oil wells, such as Los Angeles, USA, the safety radius defined in local regulations is 200 feet (60 m) [92]. Table 3 shows the buffer distances of the wells to populated areas for Salinas and La Libertad according to the equations of the DIPS methodology.

Table 3. The distances of oil wells to populated areas for Salinas and La Libertad based on the oil exploitation law and DIPS equations.

	Distance (m) Rating	
General Buffers	Salinas–La Libertad Buffers	Rating
$<x_1$	<10	5
x_2	10–14	4
x_3	14–18	3
x_4	18–30	2
x_5	30–60	1

The DIPS methodology was applied to 462 oil wells in the territory. The wells were classified as productive, temporarily abandoned, improperly abandoned, and permanently abandoned wells that were distributed in different areas, e.g., close to the sea, inside populated areas, and outside populated areas, as shown in Figure 4.

Figure 5 shows the vulnerability map obtained using the DIPS methodology for the cantons of Salinas and La Libertad. The map represents the incidence of oil wells in the territory with discrete points. Four zones where the largest wells are concentrated on the map were identified. Zone A was found to have 27 oil wells, 23 of which were highly vulnerable and 4 of which were of medium vulnerability. Zone B was found to have 30 wells, 13 of which were highly vulnerable due to their proximity to urban areas and the sea and 17 of which were of medium vulnerability. Zone C was found to have 270 wells, 78 of which had high vulnerability. Finally, zone D was found to comprise 39 wells, 14 of which were found to have high vulnerability. The wells dispersed inside La Libertad were found to be located on the outskirts of the urban areas. Figure 6 shows the vulnerability generated by the concentration of oil wells in the study area, as processed using continuous data. In this case, zones A and C showed a higher vulnerability than zones B and D, and the other areas were found to be less vulnerable to the concentration of wells.

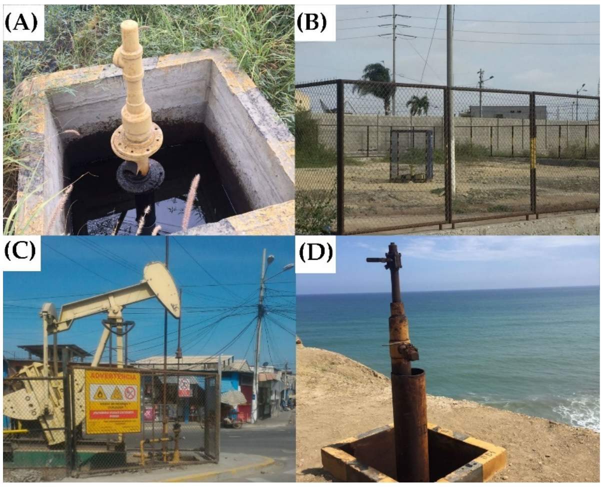

Figure 4. (**A**) Improperly abandoned well at Salinas. (**B**) Permanently abandoned well. (**C**) Productive well in a populated area of Salinas. (**D**) Improperly abandoned well near the sea.

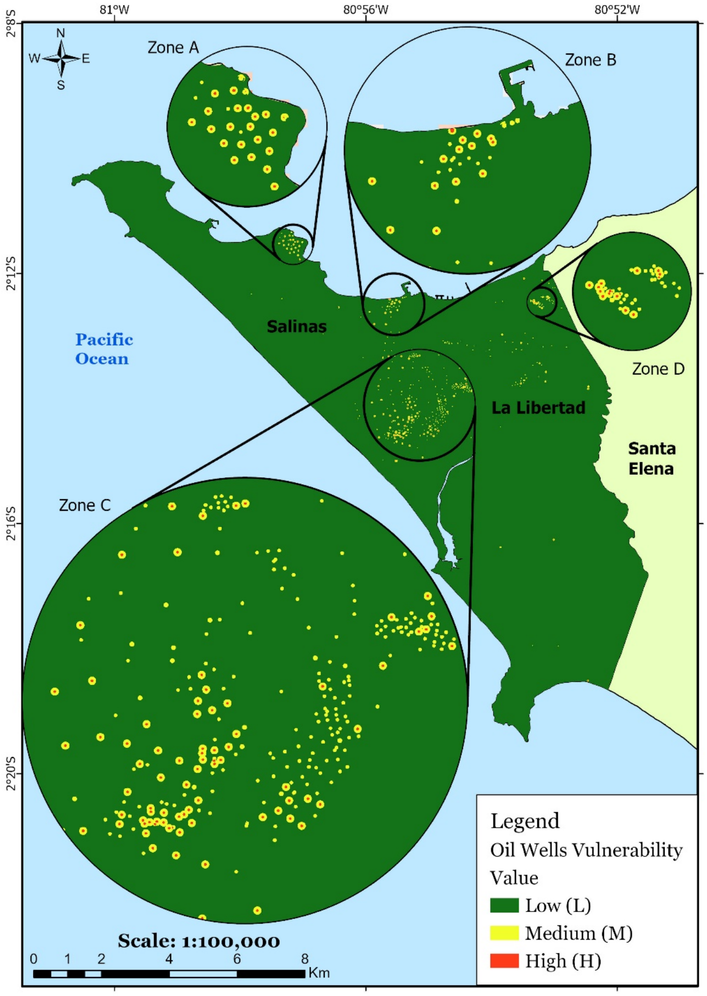

Figure 5. Application of the DIPS methodology for vulnerability in oil wells of Salinas and La Libertad. The red spots represent areas with high vulnerability, the yellow buffers represent areas of medium vulnerability, and the green area represents territory with low vulnerability.

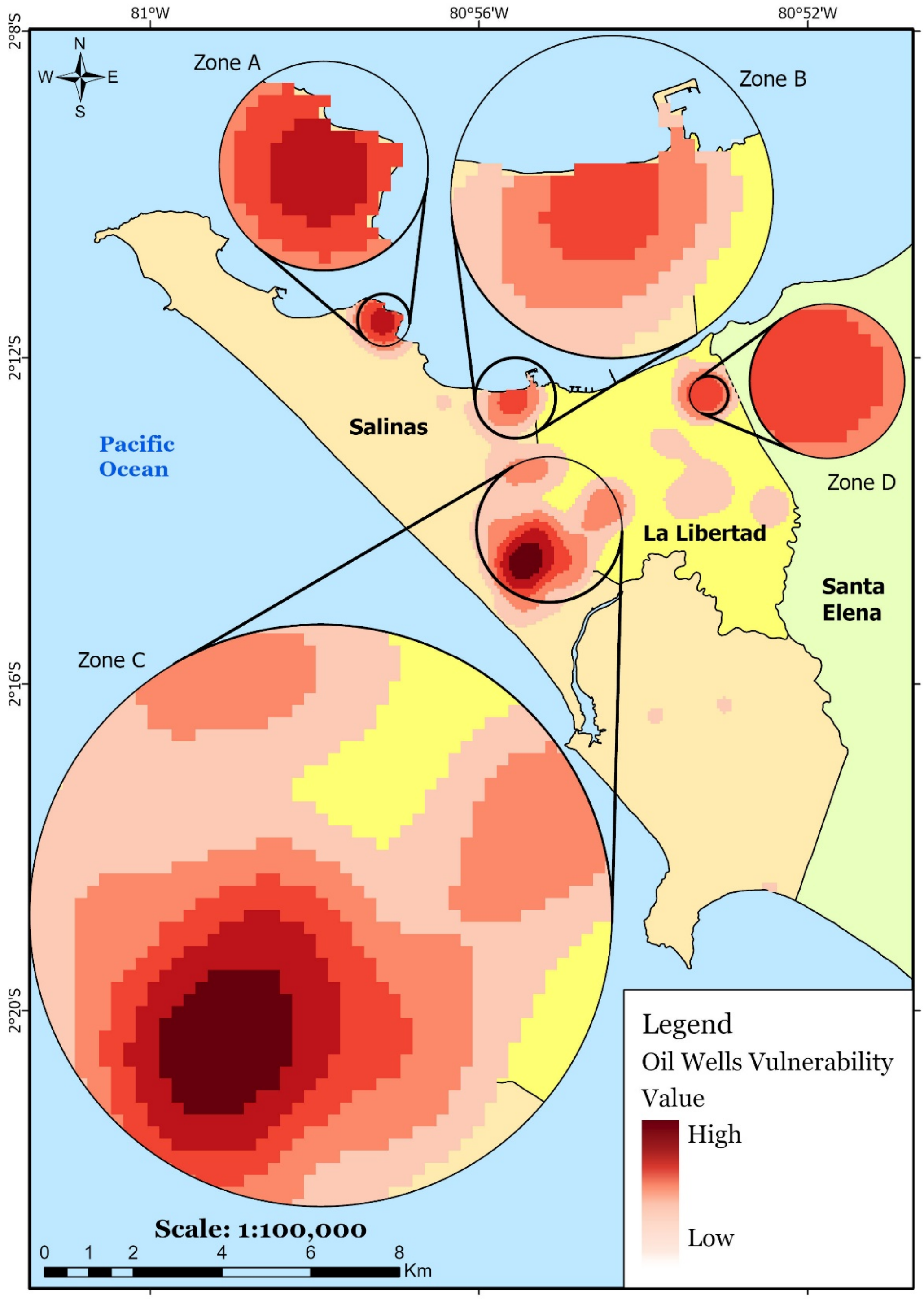

Figure 6. Map of high and low vulnerability caused by the concentration of oil wells.

4. Discussion

The DIPS methodology was designed to determine the vulnerability of populated areas within petroleum zones. In this methodology, the proximity of wells to populated areas and water bodies is given a high weighting. DIPS uses recommended characteristics of practical, quantitative, and qualitative methodologies [109,110], and it has been applied to urban areas in coastal environments using land-use strategies [111–113]. In addition, DIPS relates five variables: oil well status, soil permeability, gas perception, the distance of oil wells from the water bodies, and the distance of oil wells from urban areas. The rating of each variable depends on the exposure of the affected territory. In other words, DIPS focuses on large-scale multi-criteria evaluation that helps determine land use due to the presence of oil wells from a social and environmental point of view. One of this study's limitations was that the population distribution in the studied cantons was not considered due to the absence of this information, so resorted to using the class of "populated areas" as a tool to determine whether an area was residential. In addition, it used focus groups to assess the perception of gas emissions from oil wells.

The vulnerability map for the cantons of Salinas and La Libertad in SEP shows that 92% of the wells considered in this study are located within populated areas (Figure 5). The constant urban growth associated with population increases has led to the presence of oil wells in territories that have traditionally excluded oil activities. Moreover, the scarce security infrastructure, an absence of territorial planning, and a lack of knowledge about the risks to inhabitants have encouraged the development of these areas. Several wells are located close to water bodies and are prone to spilling hydrocarbons into beaches or the sea, so they were categorised as highly vulnerable wells. The DIPS methodology was used to identify that the Salinas canton is more vulnerable than La Libertad due to the higher concentration of wells in its urban areas and areas near the sea (Figure 6).

Vulnerability is important for land-use planning. The authors of some previous studies have analysed the potential impacts of oil spills in the vicinity of populated areas, considering both social and environmental aspects [114,115]. However, most oil assessment methods are focused on spills into marine and inland environments [12,116], as well as risk assessments for oil well and pipeline failures [117–119]. Additional methods are used to determine vulnerability. For example, DRASTIC and GOD (groundwater confinement, overlying strata, and depth to groundwater) methods assess aquifer contamination [120]. The vulnerability of aquifers to hydrocarbons can be studied via their physical properties [121,122].

The DIPS methodology considers social, technical, and environmental aspects for analysing vulnerability caused by oil wells in populated areas. This methodological approach can be applied to coastal or inland environments using GIS to integrate variables, calculate vulnerability, and process vulnerability maps. Some methodologies relating vulnerability to the oil industry are focused on oil spills in near-shore areas and involve mathematical models relating to social and environmental conditions [40–43]. Further methodologies have been used for analysing vulnerability caused by energy infrastructure and refineries in marine environments relating to social and physical conditions [54,55], as well as the vulnerability caused by oil activities due to their potential for polluting groundwater [46,47,49,123]. However, the methodology proposed in this study integrates the proximity of wells to towns and bodies of water, gas emissions, soil permeability, and well condition. Because the coastal marine zone of this research's study area is a tourist centre and in total demographic growth, it requires a territorial management strategy.

This study determined the vulnerability caused by oil wells located in coastal urban areas. The authors of previous research measured this type of risk through numerical simulations of effects generated by the explosion of a liquefied petroleum gas storage tank on a studied infrastructure and population [59]. Studies on environmental impact tend to consider citizen participation [124]. In the case of DIPS, the use of focus groups helped us to identify environmental issues affecting the community.

Various methods can be used to generate different vulnerability indexes, e.g., for natural disasters, toxicological hazards, explosions, fires, and groundwater contamination [20,24,30,125], and it is important to determine vulnerability in various areas of knowledge [126] as a mechanism for assessing the susceptibility of a system to potential risks and hazards [13,14].

The analysis of the DIPS map in this study revealed areas with a high vulnerability that require strategies to promote the development and continuous improvement of the territory [127]. The following requirements should be met: (i) oil wells must have a surrounding security infrastructure; (ii) abandoned wells must have isolation and protection infrastructure; (iii) territorial reordering that considers the critical zones detected in this work should be proposed; (iv) the population must be made aware of the risks associated with oil wells in the sector; and (v) new settlements in the vicinity of wells must be prevented.

5. Conclusions

This study evaluated the vulnerability in a populated territory with oil well incidence using the DIPS methodology, which integrates five variables (distance from oil wells to populated areas and water bodies, identification of gas perception, permeability, and state of the wells) in GIS software. DIPS enabled us to generate vulnerability maps (which are essential for decision making in territorial planning) in the service of the protection and conservation of the marine–coastal zone while favouring sustainable development. In the study area were identified 462 wells, 156 of which (34%) were shown to have high vulnerability. One hundred and fifteen of the wells with high vulnerability were found to be in the Salinas canton, with scores between 32 and 47. Within these wells, six were shown to have a higher score of between 41 and 47 due to their proximity to the coastline. In the canton of La Libertad, 39 wells presented a high vulnerability. In addition, in both Salinas and La Libertad were found 101 and 159 wells, respectively, with medium vulnerability.

The reported high vulnerability was due to the concentration of wells and gas emissions observed in zones A, B, C, and D. Additionally, the proximity of wells to the coastline influenced vulnerability, as observed in zones A and B. In urban areas, 102 wells were found to be productive, leading to fire risks and affecting the inhabitants of these sectors. Finally, it is recommended to implement: (i) protective infrastructure that prevents free access to the wells and guarantees distance and/or buffering from homes; (ii) land-use planning; (iii) protection of tourist and heritage areas; (iv) landscape management; (v) the dissemination of an education plan; (vi) changes to protection perimeters; and (vii) the monitoring of oil wells in urban areas.

Vulnerability analyses are useful because they consider variables regarding soil type, gases, distance to populated areas, environment, and human health. The DIPS methodology was developed to recommend land-use planning strategies. Our analysis enabled the identification of vulnerable areas generated by the presence and concentration of oil wells through discrete and continuous data, a process that could be applied to urban territories located near industrial activities.

Finally, our application of DIPS was focused on urban or rural centres with the presence of oil wells. Therefore, it is recommended to advise the relevant government entities to (i) identify the location of oil wells, along with their status (productive, temporarily abandoned, improperly abandoned, and permanently abandoned wells); (ii) use focus groups to identify the perception of hydrocarbon gas emissions from wells; (iii) use geodata available in different government geoportals to determine populated areas, water bodies, and soil permeability; (iv) search for legislation that determines the safety radii around wells and to use the equations described for buffers; and (v) use a geographic information systems tool for visualisation and decision making.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources11080070/s1, Table S1: Comparison of studies presenting different methodologies for the vulnerability assessment of the oil and gas industry.

Author Contributions: Conceptualisation, G.H.-F. and F.J.M.; methodology, G.H.-F., F.J.M. and A.V.-M.; software, A.V.-M.; validation, G.H.-F., F.J.M., A.V.-M. and J.C.-P.; formal analysis, G.H.-F., F.J.M., A.V.-M. and J.C.-P.; investigation, G.H.-F., F.J.M., A.V.-M. and J.C.-P.; data curation, G.H.-F., A.V.-M. and J.C.-P.; writing—original draft preparation, G.H.-F., F.J.M. and A.V.-M.; writing—review and editing, G.H.-F. and J.C.-P.; visualisation, A.V.-M.; supervision, G.H.-F. and F.J.M.; project administration, G.H.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the research projects convened from various scientific research projects, as the "Peninsula Santa Elena Geopark Project" of the UPSE University Project (Universidad Estatal Península de Santa Elena) with code no. 91870000.0000.381017; and the project "Factores geoambientales de los pozos petroleros y su Incidencia en el Desarrollo Territorial en los Cantones Salinas y La Libertad de la Provincia de Santa Elena", code no: 91870000.0000.385428. In addition, projects of the ESPOL Polytechnic University such as "Registry of geological and mining heritage and its impact on the defense and preservation of geodiversity in Ecuador" with code CIPAT-01-2018. We also would like to thank four anonymous reviewers for their constructive comments and the editorial office for the editorial handling.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Vorobev, V.; Safarov, I.; Mostovoy, P.; Shakirzyanov, L.; Fagereva, V. Best practices of exploration: Integration of seismic and electrical prospecting. In Proceedings of the SPE Annual Technology Conference Exhibition, Calgary, AB, Canada, 23 September 2019. [CrossRef]
2. Antonenko, D.A.; Islamov, R.A.; Stavinsky, P.V.; Yatsenko, V.M. A system approach to vankorskoye oilfield development planning. In Proceedings of the SPE Russian Oil Gas Technology Conference Exhibition, Moscow, Russia, 3 October 2006; Volume 2, pp. 1067–1076. [CrossRef]
3. Ruble, I. The U.S. crude oil refining industry: Recent developments, upcoming challenges and prospects for exports. *J. Econ. Asymmetries* **2019**, *20*, e00132. [CrossRef]
4. Abdou, H.A.M. Case study in upgrading capability of a crude oil pipeline for maximum transportation capacity. In Proceedings of the Society Petroleum Engineers-North Africa Technology Conference Exhibition, NATC 2013, Cairo, Egypt, 15–17 April 2013; Volume 1, pp. 203–219. [CrossRef]
5. Iwegbue, C.M.A.; Bebenimibo, E.; Tesi, G.O.; Egobueze, F.E.; Martincigh, B.S. Spatial characteristics and risk assessment of polychlorinated biphenyls in surficial sediments around crude oil production facilities in the Escravos River Basin, Niger Delta, Nigeria. *Mar. Pollut. Bull.* **2020**, *159*, 111462. [CrossRef]
6. Zhao, J.; Fan, J.; He, Y.; Yang, Z.; Gao, W.; Gao, W. Optimization of horizontal well injection-production parameters for ultra-low permeable-tight oil production: A case from Changqing Oilfield, Ordos Basin, NW China. *Pet. Explor. Dev.* **2015**, *42*, 74–82. [CrossRef]
7. Chilingar, G.V.; Endres, B. Environmental hazards posed by the Los Angeles Basin urban oilfields: An historical perspective of lessons learned. *Environ. Geol.* **2005**, *47*, 302–317. [CrossRef]
8. Shamasunder, B.; Collier-Oxandale, A.; Blickley, J.; Sadd, J.; Chan, M.; Navarro, S.; Hannigan, M.; Wong, N.J. Community-based health and exposure study around urban oil developments in South Los Angeles. *Int. J. Environ. Res. Public Health* **2018**, *15*, 138. [CrossRef] [PubMed]
9. Gatto, A.; Loewenstein, W.; Sadik-Zada, E.R. An extensive data set on energy, economy, environmental pollution and institutional quality in the petroleum-reliant developing and transition economies. *Data Br.* **2021**, *35*, 106766. [CrossRef]
10. Chandel, A.K.; Sukumaran, R.K. *Sustainable biofuels Development in India*, 1st ed.; Springer: Cham, Switzerland, 2017; pp. 1–557. [CrossRef]
11. García-Chiang, A. Corporate social responsibility in the Mexican oil industry: Social impact assessment as a tool for local development. *Int. J. Corp. Soc. Responsib.* **2018**, *3*, 1–8. [CrossRef]
12. Amir-Heidari, P.; Raie, M. Probabilistic risk assessment of oil spill from offshore oil wells in Persian Gulf. *Mar. Pollut. Bull.* **2018**, *136*, 291–299. [CrossRef]
13. Bakkensen, L.A.; Fox-Lent, C.; Read, L.K.; Linkov, I. Validating Resilience and Vulnerability Indices in the Context of Natural Disasters. *Risk Anal.* **2017**, *37*, 982–1004. [CrossRef] [PubMed]
14. Scholz, R.W.; Blumer, Y.B.; Brand, F.S. Risk, vulnerability, robustness, and resilience from a decision-theoretic perspective. *J. Risk Res.* **2012**, *15*, 313–330. [CrossRef]
15. Cutter, S.L. Vulnerability to hazards. *Prog. Hum. Geogr.* **1996**, *20*, 529–539. [CrossRef]
16. Ahsan, M.N.; Warner, J. The socioeconomic vulnerability index: A pragmatic approach for assessing climate change led risks-A case study in the south-western coastal Bangladesh. *Int. J. Disaster Risk Reduct.* **2014**, *8*, 32–49. [CrossRef]
17. Turconi, L.; Luino, F.; Gussoni, M.; Faccini, F.; Giardino, M.; Casazza, M. Intrinsic environmental vulnerability as shallow landslide susceptibility in environmental impact assessment. *Sustainability* **2019**, *11*, 6285. [CrossRef]
18. Cohen, A. The multidimensional poverty assessment tool: A new framework for measuring rural poverty. *Dev. Pract.* **2010**, *20*, 887–897. [CrossRef]
19. Suidarma, M.I.; Anggaradana, N.I.; Nengah, G.I.; Indrawati, Y. Financial System Vulnerability Indicators in Indonesia. *Int. J. Econ. Financ. Issues* **2017**, *7*, 299–306.
20. Marzo, E.; Busini, V.; Rota, R. Definition of a short-cut methodology for assessing the vulnerability of a territory in natural-technological risk estimation. *Reliab. Eng. Syst. Saf.* **2015**, *134*, 92–97. [CrossRef]

21. Guillard-Gonçalves, C.; Zêzere, J.L. Combining social vulnerability and physical vulnerability to analyse landslide risk at the municipal scale. *Geoscience* **2018**, *8*, 294. [CrossRef]
22. Yariyan, P.; Avand, M.; Soltani, F.; Ghorbanzadeh, O.; Blaschke, T. Earthquake vulnerability mapping using different hybrid models. *Symmetry* **2020**, *12*, 405. [CrossRef]
23. Yang, W.; Xu, K.; Lian, J.; Bin, L.; Ma, C. Multiple flood vulnerability assessment approach based on fuzzy comprehensive evaluation method and coordinated development degree model. *J. Environ. Manag.* **2018**, *213*, 440–450. [CrossRef]
24. Granda, S.; Ferreira, T.M. Assessing Vulnerability and Fire Risk in Old Urban Areas: Application to the Historical Centre of Guimarães. *Fire Technol.* **2019**, *55*, 105–127. [CrossRef]
25. Das, P.; Talukdar, S.; Ziaul, S.; Das, S.; Pal, S. Noise mapping and assessing vulnerability in meso level urban environment of Eastern India. *Sustain. Cities Soc.* **2019**, *46*, 101416. [CrossRef]
26. Zhao, J.; Ji, G.; Tian, Y.; Chen, Y.; Wang, Z. Environmental vulnerability assessment for mainland China based on entropy method. *Ecol. Indic.* **2018**, *91*, 410–422. [CrossRef]
27. He, L.; Shen, J.; Zhang, Y. Ecological vulnerability assessment for ecological conservation and environmental management. *J. Environ. Manag.* **2018**, *206*, 1115–1125. [CrossRef] [PubMed]
28. Sahoo, S.; Dhar, A.; Kar, A. Environmental vulnerability assessment using Grey Analytic Hierarchy Process based model. *Environ. Impact Assess. Rev.* **2016**, *56*, 145–154. [CrossRef]
29. Ho, H.C.; Wong, M.S.; Man, H.Y.; Shi, Y.; Abbas, S. Neighborhood-based subjective environmental vulnerability index for community health assessment: Development, validation and evaluation. *Sci. Total Environ.* **2019**, *654*, 1082–1090. [CrossRef] [PubMed]
30. Ghajari, Y.E.; Alesheikh, A.A.; Modiri, M.; Hosnavi, R.; Abbasi, M. Spatial modelling of urban physical vulnerability to explosion hazards using GIS and fuzzy MCDA. *Sustainability* **2017**, *9*, 1274. [CrossRef]
31. Jamshed, A.; Rana, I.A.; Mirza, U.M.; Birkmann, J. Assessing relationship between vulnerability and capacity: An empirical study on rural flooding in Pakistan. *Int. J. Disaster Risk Reduct.* **2019**, *36*, 101109. [CrossRef]
32. Torresan, S.; Critto, A.; Dalla Valle, M.; Harvey, N.; Marcomini, A. Assessing coastal vulnerability to climate change: Comparing segmentation at global and regional scales. *Sustain. Sci.* **2008**, *3*, 45–65. [CrossRef]
33. Sahoo, B.; Bhaskaran, P.K. Multi-hazard risk assessment of coastal vulnerability from tropical cyclones–A GIS based approach for the Odisha coast. *J. Environ. Manag.* **2018**, *206*, 1166–1178. [CrossRef]
34. Yu, X.; Michael, H.A. Offshore Pumping Impacts Onshore Groundwater Resources and Land Subsidence. *Geophys. Res. Lett.* **2019**, *46*, 2553–2562. [CrossRef]
35. Fatoba, P.O.; Ogunkunle, C.O.; Folarin, O.O.; Oladele, F.A. Heavy metal pollution and ecological geochemistry of soil impacted by activities of oil industry in the Niger Delta, Nigeria. *Environ. Earth Sci.* **2016**, *75*, 1–9. [CrossRef]
36. Reale, M.; Costantini, E.; D'angelo, C.; Coppeta, L.; Mangifesta, R.; Jagarlapoodi, S.; Di Nicola, M.; Di Giampaolo, L. Network between cytokines, cortisol and occupational stress in gas and oilfield workers. *Int. J. Mol. Sci.* **2020**, *21*, 1118. [CrossRef]
37. Ochege, F.U.; George, R.T.; Dike, E.C.; Okpala-Okaka, C. Geospatial assessment of vegetation status in Sagbama oilfield environment in the Niger Delta region, Nigeria. *Egypt. J. Remote Sens. Sp. Sci.* **2017**, *20*, 211–221. [CrossRef]
38. Herrera-Franco, G.; Montalván-Burbano, N.; Mora-Frank, C.; Moreno-Alcívar, L. Research in Petroleum and Environment: A Bibliometric Analysis in South America. *Int. J. Sustain. Dev. Plan.* **2021**, *16*, 1109–1116. [CrossRef]
39. Gupta, E. Oil vulnerability index of oil-importing countries. *Energy Policy* **2008**, *36*, 1195–1211. [CrossRef]
40. Castanedo, S.; Juanes, J.A.; Medina, R.; Puente, A.; Fernandez, F.; Olabarrieta, M.; Pombo, C. Oil spill vulnerability assessment integrating physical, biological and socio-economical aspects: Application to the Cantabrian coast (Bay of Biscay, Spain). *J. Environ. Manag.* **2009**, *91*, 149–159. [CrossRef] [PubMed]
41. de Andrade, M.M.N.; Szlafsztein, C.F.; Souza-Filho, P.W.M.; dos Araújo, A.R.; Gomes, M.K.T. A socioeconomic and natural vulnerability index for oil spills in an Amazonian harbor: A case study using GIS and remote sensing. *J. Environ. Manag.* **2010**, *91*, 1972–1980. [CrossRef]
42. Olita, A.; Cucco, A.; Simeone, S.; Ribotti, A.; Fazioli, L.; Sorgente, B.; Sorgente, R. Oil spill hazard and risk assessment for the shorelines of a Mediterranean coastal archipelago. *Ocean Coast. Manag.* **2012**, *57*, 44–52. [CrossRef]
43. Frazão Santos, C.; Carvalho, R.; Andrade, F. Quantitative assessment of the differential coastal vulnerability associated to oil spills. *J. Coast. Conserv.* **2013**, *17*, 25–36. [CrossRef]
44. Ghalwash, G. Elkawam Updated Oil Spill Risk Assessment for The Gulf Of Suez. In *Management Information Systems*; Brebbia, C.A., Ed.; WIT Press: Chilworth, UK, 2004; pp. 463–472; ISBN 978-1-85312-736-6.
45. Barbosa-Monteiro, C.B.; Haron, P.H.; Fagundes Leal, T.F.; Correa Marques, W.; Nicolodi, J.L.; Lopes, B.F. Integrated environmental vulnerability to oil spills in sensitive areas. *Environ. Pollut.* **2020**, *267*, 115238. [CrossRef]
46. Wang, Z.; Wu, Q.; Zhang, Y.; Cheng, J. Confined groundwater pollution mechanism and vulnerability assessment in oilfields, North China. *Environ. Earth Sci.* **2011**, *64*, 1547–1553. [CrossRef]
47. Loveless, S.E.; Lewis, M.A.; Bloomfield, J.P.; Davey, I.; Ward, R.S.; Hart, A.; Stuart, M.E. A method for screening groundwater vulnerability from subsurface hydrocarbon extraction practices. *J. Environ. Manag.* **2019**, *249*, 109349. [CrossRef] [PubMed]
48. Gemitzi, A.; Petalas, C.; Tsihrintzis, V.A.; Pisinaras, V. Assessment of groundwater vulnerability to pollution: A combination of GIS, fuzzy logic and decision making techniques. *Environ. Geol.* **2006**, *49*, 653–673. [CrossRef]

49. Zhang, H.; Lu, P.; Zhang, D.; Kou, S.; Bao, K.; Li, C.; Wang, J.; Mao, Y. Watershed-scale assessment of surface water-related risks from shale gas development in mountainous areas, China. *J. Environ. Manag.* **2021**, *279*, 111589. [CrossRef]
50. Mortamais, M.; Pujol, J.; van Drooge, B.L.; Macià, D.; Martínez-Vilavella, G.; Reynes, C.; Sabatier, R.; Rivas, I.; Grimalt, J.; Forns, J.; et al. Effect of exposure to polycyclic aromatic hydrocarbons on basal ganglia and attention-deficit hyperactivity disorder symptoms in primary school children. *Environ. Int.* **2017**, *105*, 12–19. [CrossRef]
51. Lieske, D.J.; Fifield, D.A.; Gjerdrum, C. Maps, models, and marine vulnerability: Assessing the community distribution of seabirds at-sea. *Biol. Conserv.* **2014**, *172*, 15–28. [CrossRef]
52. Fauchald, P.; Erikstad, K.E.; Systad, G.H. Seabirds and marine oil incidents: Is it possible to predict the spatial distribution of pelagic seabirds? *J. Appl. Ecol.* **2002**, *39*, 349–360. [CrossRef]
53. Golden, N.H.; Rattner, B.A. Ranking Terrestrial Vertebrate Species for Utility in Biomonitoring and Vulnerability to Environmental Contaminants. In *Reviews of Environmental Contamination and Toxicology*; Ware, G.W., Ed.; Springer: Berlin/Heidelberg, Germany, 2003; Volume 176, pp. 67–136.
54. Mohammadfam, I.; Zarei, E. Safety risk modeling and major accidents analysis of hydrogen and natural gas releases: A comprehensive risk analysis framework. *Int. J. Hydr. Energy* **2015**, *40*, 13653–13663. [CrossRef]
55. Dismukes, D.; Narra, S. Identifying the Vulnerabilities of Working Coasts Supporting Critical Energy Infrastructure. *Water* **2015**, *8*, 8. [CrossRef]
56. Wijewickreme, D.; Honegger, D.; Mitchell, A.; Fitzell, T. Seismic Vulnerability Assessment and Retrofit of a Major Natural Gas Pipeline System: A Case History. *Earthq. Spectr.* **2005**, *21*, 539–567. [CrossRef]
57. Taleb-Berrouane, M.; Khan, F.; Hawboldt, K.; Eckert, R.; Skovhus, T.L. Model for microbiologically influenced corrosion potential assessment for the oil and gas industry. *Corros. Eng. Sci. Technol.* **2018**, *53*, 378–392. [CrossRef]
58. Bajpai, S.; Gupta, J.P. Securing oil and gas infrastructure. *J. Pet. Sci. Eng.* **2007**, *55*, 174–186. [CrossRef]
59. Hassani, M.; Chaib, R.; Bouzerara, R. Vulnerability Assessment for Major Industrial Risks Proposal for a Semiquantitative Analysis Method (VAMIR) Application: Oil and Gas Industry. *J. Fail. Anal. Prev.* **2020**, *20*, 1568–1582. [CrossRef]
60. Benalcazar, F.L.; Valdivieso, S. Successful Execution of an Exploratory Drilling Program Within Extremely Sensitive Environments in Ecuador. In Proceedings of the SPE Latin American and Caribbean Petroleum Engineering Conference, Quito, Ecuador, 18–20 November 2015; Volume 1. [CrossRef]
61. Arild, O.; Ford, E.P.; Lohne, H.P.; Majoumerd, M.M.; Havlova, V. A Comparison of FEP-analysis and Barrier Analysis for CO_2 Leakage Risk Assessment on an Abandoned Czech Oilfield. *Energy Procedia* **2017**, *114*, 4237–4255. [CrossRef]
62. Schilling, J.; Akuno, M.; Scheffran, J.; Weinzierl, T. On raids and relations: Climate change, pastoral conflict and adaptation in north-western Kenya. In *Conflict-Sensitive Adaptation to Climate Change in Africa*; Bronkhorst, S., Urmilla, B., Eds.; Berliner Wissenschaftsverlag: Berlin, Germany, 2014; pp. 241–268; ISBN 978-3-8305-2010-8.
63. Schilling, J.; Locham, R.; Weinzierl, T.; Vivekananda, J.; Scheffran, J. The nexus of oil, conflict, and climate change vulnerability of pastoral communities in northwest Kenya. *Earth Syst. Dyn.* **2015**, *6*, 703–717. [CrossRef]
64. Romero, A.F.; Abessa, D.M.S.; Fontes, R.F.C.; Silva, G.H. Integrated assessment for establishing an oil environmental vulnerability map: Case study for the Santos Basin region, Brazil. *Mar. Pollut. Bull.* **2013**, *74*, 156–164. [CrossRef] [PubMed]
65. Câmara, S.F.; Pinto, F.R.; da Silva, F.R.; de Soares, M.O.; De Paula, T.M. Socioeconomic vulnerability of communities on the Brazilian coast to the largest oil spill (2019–2020) in tropical oceans. *Ocean Coast. Manag.* **2021**, *202*, 5506. [CrossRef]
66. Llerena-Montoya, S.; Velastegui-Montoya, A.; Zhirzhan-Azanza, B.; Herrera-Matamoros, V.; Adami, M.; De Lima, A.; Moscoso-Silva, F.; Encalada, L. Multitemporal analysis of land use and land cover within an oil block in the ecuadorian amazon. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 191. [CrossRef]
67. GAD Santa Elena Plan de Desarrollo y Ordenamiento Territorial-Cantón Santa Elena 2014–2019. Available online: http://app.sni.gob.ec/sni-link/sni/PORTAL_SNI/data_sigad_plus/sigadplusdiagnostico/0960001540001_PlandeDesarrolloyOrdenamientoTerritorial30-01-2015-2fin_19-02-2015_09-41-20.pdf (accessed on 8 August 2021).
68. GAD La Libertad Plan de Desarrollo y Ordenamiento Territorial. Available online: http://app.sni.gob.ec/sni-link/sni/PORTAL_SNI/data_sigad_plus/sigadplusdiagnostico/0960006340001_DiagnosticoCantonLaLibertad_14-03-2015_20-08-55.pdf (accessed on 8 August 2021).
69. Inec Proyección De La Población Ecuatoriana, Por Años Calendario, Según Cantones 2010-2020. Available online: https://www.obraspublicas.gob.ec/wp-content/uploads/downloads/2017/03/proyeccion_cantonal_total_2010-202012016-v1.pdf (accessed on 29 September 2021).
70. Mestanza, C.; Botero, C.M.; Anfuso, G.; Chica-Ruiz, J.A.; Pranzini, E.; Mooser, A. Beach litter in Ecuador and the Galapagos islands: A baseline to enhance environmental conservation and sustainable beach tourism. *Mar. Pollut. Bull.* **2019**, *140*, 573–578. [CrossRef]
71. Estrada, J. *Ancón En La Historia Petrolera Del Ecuador 1911-1976*; ESPOL: Guayaquil, Ecuador, 2001; ISBN 9978-41-794-X.
72. Moreno, J.; Sevillano, G.; Valverde, O.; Loayza, V.; Haro, R.; Zambrano, J. Soil from the Coastal Plane. In *The Soils of Ecuador*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 27–77; ISBN 9783319253190.
73. Bengtson, N.A. Some essential features of the geography of the santa elena peninsula, ecuador. *Ann. Assoc. Am. Geogr.* **1924**, *14*, 150–158. [CrossRef]

74. Herrera-Franco, G.; Carrión-Mero, P.; Alvarado, N.; Morante-Carballo, F.; Maldonado, A.; Caldevilla, P.; Briones-Bitar, J.; Berrezueta, E. Geosites and georesources to foster geotourism in communities: Case study of the santa elena peninsula geopark project in Ecuador. *Sustainability* **2020**, *12*, 4484. [CrossRef]
75. Herrera-Franco, G.; Erazo, K.; Mora-Frank, C.; Carrión-Mero, P.; Berrezueta, E. Evaluation of a Paleontological Museum as Geosite and Base for Geotourism. A Case Study. *Heritage* **2021**, *4*, 67. [CrossRef]
76. Jaillard, É.; Ordoñez, M.; Benitez, S.; Berrones, G.; Jiménez, N.; Montenegro, G.; Zambrano, I. Basin Development in an Accretionary, Oceanic-Floored Fore-Arc Setting: Southern Coastal Ecuador During Late Cretaceous-Late Eocene Time. In *Petroleum Basins of South America*, 1st ed; Tankard, A.J., Suárez Soruco, R., Welsink, H.J., Eds.; American Association of Petroleum Geologists: Tulsa, OK, USA, 1995; Volume 62, pp. 615–631. [CrossRef]
77. Antenor Alemán, M.; Montenegro, G.; Palencia, A.; Lezama, E. Comentario al artículo "Correlación geoquímica entre crudos y rocas del sistema petrolero de la península de Santa Elena y el golfo de Guayaquil" por Lorenzo et al. *Bol. Geol.* **2019**, *41*, 151–157. [CrossRef]
78. Nuñez, E.; Dugas, F. Guía Geológica del Suoreste de la Costa Ecuatoriana. *J. Chem. Inf. Model.* **1986**, *53*, 1689–1699.
79. Higley, D.K. The Progreso Basin Province of Northwestern Peru and Sothwestern Ecuador: Neogene and Cretaceous-Paleogene Total Petroleum Systems. In *USA Geological Survey Bulletin 2206-B*; USA Department of the Interior: Washington, DC, USA, 2004.
80. Petroecuador, E. El petróleo: Su formación, desarrollo y mercado. In *El Petróleo En El Ecuador Nueva Era Petrolera*; Gobierno de Ecuador: Quito, Ecuador, 2013; pp. 13–33.
81. Rashid, A.K.M.M. Understanding Vulnerability and Risks. In *Disaster Risk Reduction*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 23–43. ISBN 9784431542520.
82. Dewan, A.M. *Floods in a Megacity: Geospatial Techniques in Assessing Hazards, Risk and Vulnerability*; Springer: Berlin/Heidelberg, Germany, 2013; ISBN 9789400758759.
83. Barrios, M.; Guilera, G.; Nuño, L.; Gómez-Benito, J. Consensus in the delphi method: What makes a decision change? *Technol. Forecast. Soc. Chang.* **2021**, *163*, 120484. [CrossRef]
84. Aller, L.; Bennett, T.; Lehr, J.H.; Petty, R.J.; Hackett, G. *DRASTIC: A Standardized Method for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings*; NWWA/Epa-600/2-87-035; Robert, S., Ed.; Kerr Environmental Research Laboratory: Ada, OK, USA, 1987; p. 455.
85. Hignett, S.; McDermott, H. Qualitative Methodology. In *Evaluation of Human Work*; Taylor & Francis Group: Boca Raton, FL, USA, 2015; pp. 119–138. ISBN 9781466559615.
86. Scholl, A. Quantitative methodology. *Int. Encycl. Commun.* **2015**, *1*, 67–74. [CrossRef]
87. ESRI ArcGis Pro. Environmental Systems Research Institute, Inc. (ESRI), California, United States. Available online: https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview (accessed on 18 December 2021).
88. Huang, L.; Wang, Y.; Pei, S.; Cui, G.; Zhang, L.; Ren, S.; Zhang, Z.; Wang, N. Effect of elevated pressure on the explosion and flammability limits of methane-air mixtures. *Energy* **2019**, *186*, 115840. [CrossRef]
89. Kang, M.; Kanno, C.M.; Reid, M.C.; Zhang, X.; Mauzerall, D.L.; Celia, M.A.; Chen, Y.; Onstott, T.C. Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 18173–18177. [CrossRef]
90. MAE Mapa Interactivo. Available online: http://ide.ambiente.gob.ec/mapainteractivo/ (accessed on 18 December 2021).
91. Gad La Libertad La Ordenanza Que Regula El Uso Del Suelo Y El Desarrollo Urbano En Zonas De Actividad Hidrocarburífera En El Cantón. Available online: Lalibertad.gob.ec/municipio/clases/download/ley/descarga/3610.pdf (accessed on 10 October 2021).
92. Los Angeles Municipal Code Sec. 91.6105. Separation from Oil Wells. Available online: https://codelibrary.amlegal.com/codes/los_angeles/latest/lamc/0-0-0-176574#JD_91.6105 (accessed on 8 August 2021).
93. Carter, H.H.; Najarian, T.O.; Pritchard, D.W.; Wilson, R.E. The dynamics of motion in estuaries and other coastal water bodies. *Rev. Geophys.* **1979**, *17*, 1585. [CrossRef]
94. Lindegaard, C. Classification of water-bodies and pollution. In *The Chironomidae*; Springer: Dordrecht, The Netherlands, 1995; pp. 385–404.
95. Lebel, E.D.; Lu, H.S.; Vielstädte, L.; Kang, M.; Banner, P.; Fischer, M.L.; Jackson, R.B. Methane Emissions from Abandoned Oil and Gas Wells in California. *Environ. Sci. Technol.* **2020**, *54*, 14617–14626. [CrossRef]
96. Christian, S.; Celia, M.A.; Mauzerall, D.L.; Bill, M.; Miller, A.R.; Chen, Y.; Conrad, M.E.; Darrah, T.H.; Jackson, R.B. Correction: Identification and characterization of high methane-emitting abandoned oil and gas wells. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 13636–13641. [CrossRef]
97. Kumar, N.; Gupta, H. Methane: Risk assessment, environmental, and health hazard. In *Hazard. Gases*, 1st ed.; Singh, J., Kaushik, R.D., Chawla, M., Eds.; Academic Press: London, UK, 2021; pp. 225–238. [CrossRef]
98. McKain, K.; Down, A.; Raciti, S.M.; Budney, J.; Hutyra, L.R.; Floerchinger, C.; Herndon, S.C.; Nehrkorn, T.; Zahniser, M.S.; Jackson, R.B.; et al. Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 1941–1946. [CrossRef] [PubMed]
99. Herrera-Franco, G.; Escandón-Panchana, P.; Erazo, K.; Mora-Frank, C.; Berrezueta, E. Geoenvironmental analysis of oil extraction activities in urban and rural zones of Santa Elena Province, Ecuador. *Int. J. Energy Prod. Manag.* **2021**, *6*, 211–228. [CrossRef]
100. Dejam, M.; Hassanzadeh, H.; Chen, Z. Pre-Darcy Flow in Porous Media. *Water Resour. Res.* **2017**, *53*, 8187–8210. [CrossRef]

101. McMahon, P.B.; Thomas, J.C.; Crawford, J.T.; Dornblaser, M.M.; Hunt, A.G. Methane in groundwater from a leaking gas well, Piceance Basin, Colorado, USA. *Sci. Total Environ.* **2018**, *634*, 791–801. [CrossRef]
102. Rice, A.K.; Lackey, G.; Proctor, J.; Singha, K. Groundwater-quality hazards of methane leakage from hydrocarbon wells: A review of observational and numerical studies and four testable hypotheses. *WIREs Water* **2018**, *5*, 1–18. [CrossRef]
103. Ministerio De Agricultura Y Ganadería Archivos De Información Geográfica. Available online: https://sni.gob.ec/coberturas (accessed on 8 August 2021).
104. Freeze, R.A.; Cherry, J.A. *Groundwater*, 1st ed.; Brenn, K., McNeily, K., Eds.; Prentice-Hall: Hoboken, NJ, United States, 1979; ISBN 0133653129.
105. Kaiser, M.J. Well Trends and Structure Inventory. In *Decommissioning Forecasting and Operating Cost Estimation*, 1st ed.; Kaiser, M.J., Ed.; Gulf Professional Publishing: Cambridge, MA, USA, 2019; pp. 135–154. [CrossRef]
106. King, G.E.; Valencia, R.L. Environmental risk and well integrity of plugged and abandoned wells. In Proceedings of the Spe Annual Technology Conference Exhibition, Amsterdam, The Netherlands, 27 October 2014; Volume 6, pp. 4852–4868. [CrossRef]
107. Vera San Martín, T.; Rodriguez Rosado, G.; Arreaga Vargas, P.; Gutierrez, L. Population and building vulnerability assessment by possible worst-case tsunami scenarios in Salinas, Ecuador. *Nat. Hazards* **2018**, *93*, 275–297. [CrossRef]
108. Carvache-Franco, W.; Carvache-Franco, M.; Carvache-Franco, O.; Hernández-Lara, A.B. Motivation and segmentation of the demand for coastal and marine destinations. *Tour. Manag. Perspect.* **2020**, *34*, 100661. [CrossRef]
109. Carrión-Mero, P.; Loor-Oporto, O.; Andrade-Ríos, H.; Herrera-Franco, G.; Morante-Carballo, F.; Jaya-Montalvo, M.; Aguilar-Aguilar, M.; Torres-Peña, K.; Berrezueta, E. Quantitative and Qualitative Assessment of the "El Sexmo" Tourist Gold Mine (Zaruma, Ecuador) as A Geosite and Mining Site. *Resources* **2020**, *9*, 28. [CrossRef]
110. McCusker, K.; Gunaydin, S. Research using qualitative, quantitative or mixed methods and choice based on the research. *Perfusion* **2015**, *30*, 537–542. [CrossRef]
111. Herrera-Franco, G.; Carrión-Mero, P.; Aguilar-Aguilar, M.; Morante-Carballo, F.; Jaya-Montalvo, M.; Morillo-Balsera, M.C. Groundwater Resilience Assessment in a Communal Coastal Aquifer System. The Case of Manglaralto in Santa Elena, Ecuador. *Sustainability* **2020**, *12*, 8290. [CrossRef]
112. Pawlowski, S.D. The Delphi Method as a Research Tool: An Example, Design Considerations and Applications 1 Introduction 2 Overview of the Delphi method. *Inf. Manag.* **2004**, *42*, 15–29.
113. Pásková, M. Can indigenous knowledge contribute to the sustainability management of the aspiring rio coco geopark, Nicaragua? *Geoscience* **2018**, *8*, 277. [CrossRef]
114. McKenzie, L.M.; Allshouse, W.B.; Burke, T.; Blair, B.D.; Adgate, J.L. Population Size, Growth, and Environmental Justice Near Oil and Gas Wells in Colorado. *Environ. Sci. Technol.* **2016**, *50*, 11471–11480. [CrossRef] [PubMed]
115. Nelson, J.R.; Grubesic, T.H. Oil spill modeling. *Prog. Phys. Geogr. Earth Environ.* **2018**, *42*, 112–127. [CrossRef]
116. French-McCay, D.; Crowley, D.; Rowe, J.J.; Bock, M.; Robinson, H.; Wenning, R.; Walker, A.H.; Joeckel, J.; Nedwed, T.J.; Parkerton, T.F. Comparative Risk Assessment of spill response options for a deepwater oil well blowout: Part 1. Oil spill modeling. *Mar. Pollut. Bull.* **2018**, *133*, 1001–1015. [CrossRef]
117. Shabarchin, O.; Tesfamariam, S. Internal corrosion hazard assessment of oil & gas pipelines using Bayesian belief network model. *J. Loss Prev. Process Ind.* **2016**, *40*, 479–495. [CrossRef]
118. Patel, H.; Salehi, S. Structural integrity of liner cement in oil & gas wells: Parametric study, sensitivity analysis, and risk assessment. *Eng. Fail. Anal.* **2021**, *122*, 105203. [CrossRef]
119. Zhang, P.; Qin, G.; Wang, Y. Risk Assessment System for Oil and Gas Pipelines Laid in One Ditch Based on Quantitative Risk Analysis. *Energies* **2019**, *12*, 981. [CrossRef]
120. Ghazavi, R.; Ebrahimi, Z. Assessing groundwater vulnerability to contamination in an arid environment using DRASTIC and GOD models. *Int. J. Environ. Sci. Technol.* **2015**, *12*, 2909–2918. [CrossRef]
121. Atakpo, E.A.; Ayolabi, E.A. Evaluation of aquifer vulnerability and the protective capacity in some oil producing communities of western Niger Delta. *Environmentalist* **2009**, *29*, 310–317. [CrossRef]
122. Preston, T.M.; Chesley-Preston, T.L.; Thamke, J.N. A GIS-based vulnerability assessment of brine contamination to aquatic resources from oil and gas development in eastern Sheridan County, Montana. *Sci. Total Environ.* **2014**, *472*, 1152–1162. [CrossRef] [PubMed]
123. Besser, H.; Hamed, Y. Causes and risk evaluation of oil and brine contamination in the Lower Cretaceous Continental Intercalaire aquifer in the Kebili region of southern Tunisia using chemical fingerprinting techniques. *Environ. Pollut.* **2019**, *253*, 412–423. [CrossRef]
124. Morgan, R.K. Environmental impact assessment: The state of the art. *Impact Assess. Proj. Apprais.* **2012**, *30*, 5–14. [CrossRef]
125. Boulabeiz, M.; Klebingat, S.; Agaguenia, S. A GIS-Based GOD Model and Hazard Index Analysis: The Quaternary Coastal Collo Aquifer (NE-Algeria). *Groundwater* **2019**, *57*, 166–176. [CrossRef] [PubMed]
126. Toro, J.; Duarte, O.; Requena, I.; Zamorano, M. Determining Vulnerability Importance in Environmental Impact Assessment. The case of Colombia. *Environ. Impact Assess. Rev.* **2012**, *32*, 107–117. [CrossRef]
127. Herrera-Franco, G.; Carrión-Mero, P.; Morante-Carballo, F.; Herrera-Narváez, G.; Briones-Bitar, J.; Torrens, R.B. Strategies for the development of the value of the mining-industrial heritage of the Zaruma-Portovelo, ecuador, in the context of a geopark project. *Int. J. Energy Prod. Manag.* **2020**, *5*, 48–59. [CrossRef]