An approach to environmental sensitivity index study at coastal area toward oil spill accident: A case study on the northern and southern coast of Madura Island

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Abstract. Coastal resources and their local community economic activities are prone to oil spills pollution from tanker accidents or unappropriated operational procedures from the oil and gas industry. This study was aimed to develop supporting a prevention strategy to minimize damage and to ensure vulnerable natural resources and the local community in coastal areas are protected. Two methodologies applied to perform an integrated Environmental Sensitivity Index (ESI) named IPIECA (International Petroleum Industry Environmental Conservation Association) method and methodology that was developed by an expert from the Center of Coastal and Marine Resources Studies, IPB University (CESI, Composite ESI). The area study was located in the coastal area of Madura Island, East Java Province. Various ecosystems, shoreline types, and coastal area utilizing types have resulted in many combinations of ESI. The highest level of sensitivity will be prompted by the existence of an important ecosystem and economically land use utilizing. The important ecosystems, such as mangrove ecosystems, will result in more sensitive areas in IPIECA criteria than in CESI criteria. Consistently, in terms of socio-economic activities, land use, which has high production value and a high amount of persons employed, will be categorized as a very sensitive area.

1. Introduction

Awareness of the importance of protecting the coastal and marine environment due to the occurrence of oil spills increased again after the occurrence of a large and very bad oil spill that occurred in the Gulf of Mexico on April 20, 2010. Approximately 5000 barrels of crude oil per day polluted the waters of the Gulf of Mexico and spread towards the coast. This disaster rivaled the 1989 Exxon Valdez oil spill [1]. Besides, the degradation of the environment and human life can occur slowly and continuously. Increased industrial activity, international trade, extraction of natural resources, and pressure on population also contribute to the increased disruption on natural resources and coastal communities. The disturbance
includes pollution of coastal ecosystems and consequently lead to habitat degradation. It is important to realize that the complexity of the environment and natural resources and the potential threats to them will make natural areas and ecosystems under pressure in the future.

The oil spill or oil pollution that occurs will greatly depend on the type of ecosystems and economic activities affected, both in coastal areas and in sea waters. Each type of ecosystem and economic activity will have different levels of importance. Therefore, identifying the level of sensitivity of ecosystems and economic activities in coastal and marine areas that potentially can be affected by oil and gas activities in the region is important.

For the needs of planning and managing natural resources in coastal areas, the availability of coastal resources database plays an important role. One application of the database of natural and environmental resources is to set the level of sensitivity of the coastal environment toward oil pollution due to malfunction operational in production and the accident of oil transportation by tankers.

The main objective of the study is to identify the characteristics of environmental sensitivity through mapping natural resources in the northern and southern coastal areas of Madura Island. This study was produced in-depth information about coastal resources that have important value and, at the same time, assess their sensitivity to oil pollution occasions as well as their influence on the socio-economic conditions of the communities around the study area. More broadly, this study aims to minimize environmental damage through the efficiency and prioritization of appropriate allocations for the use of limited oil pollution prevention facilities. Furthermore, a comparison of the results of the ESI mapping between the Composite Environmental Sensitivity Index (CESI) [2, 3] and International Petroleum Industry Environmental Conservation Association (IPIECA) [4] methods is carried out. In the end, it can be seen which method is more detailed data in producing ESI maps or which ones are easier to implement in the Oil Spill Contingency Plan (OSCP) program.

2. Method

2.1. Study area

This Environmental Sensitivity Index Mapping was conducted on the north and south coast of Madura Island, East Java Province (Figure 1). The environmental profiles of north Madura coastal areas are directly faced with the Java Sea and affected by dynamic climate and oceanographic such as wind flow, sea current, tidal type, and monsoon. A sensitive ecosystem such as the mangrove ecosystem found along Bangkalan District. Mangrove ecotourism area is established at the Sepuluh sub-district. The coral reef ecosystem found at a small island, namely “Karang Jamuang”, located at Western Madura Island. Land use utilization along northern Madura Island are consists of fish or shrimp pond, salt pond, the agricultural field, human settlement, tourism area. Fish/shrimp pond and salt pond area sensitive area against oil pollution. The offshore area is utilized by the local community as a fishing ground. Oil and gas platforms also exist in this area.

On the other hand, the Southern Madura coastal area is located at Madura strait, between Madura Island and Java Island (East Java). The environmental profiles of the Southern Madura coastal area are relatively less influenced by oceanographic characteristics of the Java Sea. Mangrove ecosystem found at some rivers mouth, and shoreline types are dominated by the muddy beach. Coral reef ecosystem found in small areas such as at Gili Raja. Local economic activities that take place along coastal areas consist of the salt pond, the agricultural field, shrimp pond, and human settlement.

For mapping of the coastal area according to the level of environmental sensitivity to the occurrence of oil spills, the coastal area is segmented into several units’ analysis. Determination of the length and breadth of one unit of analysis is based on consideration of homogeneity in both coastal geomorphology and the distribution of coastal resources. Each unit of analysis then transformed into GIS-based environmental sensitivity analysis on a scale of 1: 25,000.
2.2. ESI analysis

ESI analysis was carried out with two approaches, namely (1) the approach refers to the IPIECA (International Petroleum Industry Environmental Conservation Association) criteria and (2) an approach to the criteria developed by CCMRS IPB, namely Composite Environmental Sensitivity Index (CESI). All environment thematic data are stored in the spatial database and analyzed using ArcGIS 10.5 software.

2.2.1. CESI method. This ESI study was applied as a temporal approach to the developed Environmental Sensitivity Index map. The consideration is that some themes of resources such as capture fisheries and salt farms have different resource utilization characteristics in each season. The theme of capture fisheries has different characteristics in 4 seasons, namely the West Season, the transition from West Season to East Season, East Season, and the transition of the East to West Season. Whereas salt ponds operate throughout the dry season, while during the rainy season, there is no activity or switching functions into fish ponds. Another thematic one that has a certain period is the home range of marine animals, such as the Whale Shark.

This study approach includes three very important resource systems, namely: (1) the vulnerability of coastal resources against oil pollution, (2) coastal and marine resource systems (ecological systems), and (3) social community systems (social systems). In this study, ESI was built using the equation that combines two resource systems. ESI analysis was initiated using an approach carried out by NOAA (National Oceanic and Atmospheric Administration) [5].
ESI analysis is developed based on the principle of using three components, then is arranged into three indexes, namely: Vulnerability Index (VI), Ecological Index (EI), and Social Index (SI). The Composite Environmental Sensitivity Index (CESI) is determined using the following formula:

$$CESI = \frac{1}{3} (VI + EI + SI)$$

Where:
- CESI = Combined/composite of environmental sensitivity index for each environmental variable i;
- VI = Vulnerability Index;
- EI = Ecological Index;
- SI = Social Index.

Based on the above equation, the sensitivity of each coastal theme is determined based on the characters of three functions. The results of the ESI analysis are then projected in the form of an integrated spatial display using the application of Geographical Information System software, namely ArcGIS 10.5. The ESI analysis is based on the method and technique of calculating the sensitivity index value used by CCMRS-IPB referred to NOAA. The Vulnerability Index (VI) criteria used are the criteria developed by Sloan [6].

Table 1. Sensitivity level based on ESI value.

| ESI | Sensitivity Level     |
|-----|-----------------------|
| 1   | Not Sensitive         |
| 2   | Less Sensitive        |
| 3   | Moderate              |
| 4   | Sensitive             |
| 5   | Very Sensitive        |

2.2.1.1. Thematic ESI analysis

a. Shoreline Type

The criteria for the shoreline type is determined based on the characteristic of shoreline type, and its ecological and economic values of shoreline utilization. Muddy shoreline type inhabited by mangrove has the highest index, whereas a rocky shore has the lowest index.

b. Mangrove

Among other important ecosystems, mangrove has the highest index (5) of vulnerability against oil spills [6]. Ecological resource analysis of mangrove use parameters of density, number of species, species diversity, tidal exposure, protected area, and number of wildlife. Social value is calculated based on criteria of the potential tourism development area, fishing ground, and other mangrove utilization, such as for construction/housing materials. Economic value is calculated based on the resource economic approach.

c. Coral Reef Ecosystem

The vulnerability index of the coral reef is categorized into four (4) scoring criteria [6]. The ecology criteria of coral reef based on coral percentage coverage, coral diversity, coral landscape, and the presence of protected species within a specific radius or distance between the coral reef and project activities (e.g., shipping lanes/route). Social value for the utilization of the coral reef ecosystem.

d. Capture Fisheries

The criteria for the vulnerability and ecological index for capture fisheries theme is determined by the type of fishing gear (active or passive gear) and category of fish catch (fish, shells, or shrimp). The social value of capture fisheries is defined based on the criteria of fishing gear selectivity and the number of fishermen, while the economic value of capture fisheries is defined based on the frequency of catch (trip) and fishing cost.
e. Shrimp/fish/salt pond
The vulnerability index of shrimp/fish/salt pond is categorized into five scorings [6]. Ecological criteria for fish/shrimp pond activities based on the type of aquaculture technology and fish/shrimp commodity cultured. The social value defined based on the period and the number of shrimp/fish farmers. The economic value of shrimp/fish/salt pond is defined based on aquaculture technology and production cost.

f. Tourism
The vulnerability index for tourism is determined by access from the water (%); the Ecological Index is determined by the level of natural aesthetics (%). In contrast, the Social Index is determined by the importance of activity, the number of visitors, revenue, and duration of interruption degrees of pollution.

g. Agricultural Field
The vulnerability index of the agricultural field and ecological index is determined as 3 (Based on Sloan [6]). The social index of the agricultural field is based on the percent of farmers and some cultivated commodities.

h. Human Settlement
The vulnerability index of the settlement is defined based on the percentage of houses located on the shoreline. The ecological value of the settlement is defined based on the availability of fresh water supply for the inhabitants. The social value of the settlement is defined based on a social characteristic such as human population density.

2.2.2. IPIECA (International Petroleum Industry Environmental Conservation Association) method

2.2.2.1. Shoreline type mapping. According to IPIECA [4], ESI ranking varies from 1 (very low) such as exposed rocky shore to 10 (very high) such as swamp and mangrove. The sensitivity of shoreline type then simplified into five ranks, as presented in Table 2.

| ESI (1 – 10) | Simplified ESI | Mapping of simplified ESI |
|--------------|----------------|--------------------------|
| Index 1 and 2 | ----→ 1 (Very Low) | 1 (Very Low) |
| Indexes 3, 4, 5, and 6 | ----→ 2 (Low) | 2 (Low) |
| Index 7 | ----→ 3 (Medium) | 3 (Medium) |
| Index 8 | ----→ 4 (High) | 4 (High) |
| Index 9 and 10 | ----→ 5 (Very High) | 5 (Very High) |
Source: IPIECA [4].

2.2.2.2. Mapping of biodiversity and its sensitivity elements. Mapping areas that are biodiversity-important includes the species, habitat, and natural resources affected by oil pollution must also be considered. IPIECA (2011) categorizes the biodiversity sensitivity elements are which include:
- Protection areas and areas with high biodiversity.
- Various types of habitat/ecosystem.
- Species protected those identified using the IUCN Red List and legislation in Indonesia

The sensitivity level of biodiversity is determined by the combination of the diversity of sensitive species and the sensitivity of species or protected area, as presented in Table 3.
Table 3. Ranking of the sensitive ecosystem and natural resources.

| Sensitivity of species or protected area | Very High | High | Medium | Low | Very Low |
|----------------------------------------|----------|------|--------|-----|----------|
| Diversity of sensitive species (on the same area) | Very High | High | Medium | Low | Very Low |

Source: IPIECA [4].

2.2.2.3. **Mapping socio-economic sensitivity.** According to IPIECA [4], the ranking of the sensitive areas of human use resources, which could be affected directly or indirectly by a spill, is conducted through a similar approach that has been applied for biological resources. Various parameters are available to rank socio-economic features, some parameters used are 1) the importance of the activity; 2) the number of personnel employed; 3) the revenue; 4) the duration of the interruption.

3. **Results and discussion**

Calculation results of the sensitivity levels, both based on the CESI method and the IPIECA method, are presented in Figure 2. The more unit analysis with the highest category indicates that the study area is very susceptible to oil pollution. Figure 2 also shows the distribution of units of analysis in 5 sensitivity categories levels. The highest and lowest categories have fewer units of analysis than the other categories.

In the northern coast of Madura Island, the highest sensitivity category which is the top priority in the oil spill prevention program has relatively few units of analysis refer to six units of analysis (2.58%) in the IPIECA criteria and 15 units of analysis (6.44%) on the CESI criteria. Based on this, it is known that the CESI method criteria produce more areas with the highest environmental sensitivity level categories than the IPIECA method. The theme of land use, which has the highest level of sensitivity, is muddy beaches, tourist areas, and settlements. The area with the widest number of units of analysis on the IPIECA method is the categories with "Medium" sensitivity with a total of 81 units of analysis (34.76%). Whereas in the CESI method, the "Less Sensitive" of sensitivity level dominated the study area with a total of 87 units of analysis (37.74%). The theme of land use that has a medium sensitivity level is to capture fisheries and settlements. While the theme of land use that has a "Less Sensitive" sensitivity level is capture fisheries in the period January - March in an area of more than four nautical miles.

Meanwhile, in the southern coast of Madura Island, the highest sensitivity level consists of 74 units of analysis (29.96%) based on the IPIECA method (dominated by shoreline type as mangrove) and 31 units of analysis (12.55%) based on the CESI method (dominated by salt pond land-use area). The area with the widest number units of analysis on the IPIECA method is the "High" level of sensitivity, with a total of 73 units of analysis (29.55%). Whereas in the CESI method, the "Moderate" level of sensitivity is dominated the study area with a total of 121 units of analysis (48.99%).
Figure 2. Sensitivity comparison of ESI analysis results based on (A) CESI method; (B) IPIECA method.

The area with the existence of important coastal ecosystem types such as mangroves with a large number of polygons would have a higher number of the highest sensitivity value based on the IPIECA method compared to the CESI method. The CESI method, such a condition will produce data mode (data that often appears) in the range of “Sensitive” and “Moderate”.

ESI mapping results at the study area presented in Figure 3, show that the application of the ESI method based on the IPIECA method gives the results of areas with “High” and “Very High” sensitivity levels are more dominant in the south coastal area of Madura Island compared to the northern coast of Madura Island. While based on the CESI method, areas with a “Moderate” sensitivity level are more dominant in the offshore area (fishing ground area) both the northern and southern coastal areas of Madura Island.
Figure 3. ESI map coastal area of Madura Island. (A) based on the IPIECA method; (B) based on the CESI method.
The shoreline along the Southern coast of Madura Island is dominated by muddy type and inhabited by mangrove, resulting in a very high level of sensitivity both by the IPIECA and CESI methods. On the other hand, shoreline type in northern Madura is predominantly sandy and rocky beaches as a typical feature of the beach facing the open sea. Hence, the sensitivity class is lower than that of the southern of Madura Island, resulted in a sensitivity class of “Moderate”/“Medium”.

Most of the shoreline types of the southern coast of Madura Island is inhabited by mangroves. The existence downstream river on the southern coast of Madura Island transports material from the upland and creates the river estuary, a suitable place for the mangrove ecosystem. The dominant substrate of mud with high organic material at the estuary is very suitable for mangrove to grow. Based on the IPIECA method, the mangrove theme is indicated the highest level of sensitivity (“Very High”), while the CESI Method is grouped in two classes, namely “Very Sensitive” and “Moderate”. Whereas mangroves on the northern coast of Madura Island grow on varied shoreline types areas, including mud, sandy, and rocky beaches, resulting in more variability in ecological characteristics and resulted in varying ESI values both on IPIECA method and CESI method.

The study area is not an ideal area for coral reef growth due to high sedimentation, resulting in high water turbidity. As a consequence, there is a limited area that has coral reef ecosystems. Both IPECA and CESI Methods, analysis of sensitivity level, resulted in a level of “Moderate”/“Medium”.

The shrimp/fish pond area in the coastal area of the south of Madura Island is more spatially spread than that of the northern coast of Madura Island, which is more concentrated only in several locations. Aquaculture technology applied is in the range from traditional to intensive to produce the expected volume of fish/shrimp production. The ESI calculation shows that the sensitivity level is in range of “Moderate”/“Medium” to “Very sensitive”/“Very high”. The most frequent levels of sensitivity are at the “Sensitive” and “Medium”.

Salt ponds in the coastal area of Madura Island are the main salt producer in Indonesia with a large harvest volume, resulting in high socio-economic value and create sensitivity class in the range of “High”/“Sensitive” to “Very high”/“Very Sensitive”. Salt pond area on the southern coast of Madura Island spread along the coastline, especially in Sumenep District that has the highest production of salt. While on the northern coast of Madura Island, salt pond area is only concentrated in several locations such as in Klampis, Sepuluh, and Tanjung Bumi in Bangkalan District and Lombang, Sumenep District.

The tourism area both on the northern and the southern coast of Madura Island has not been managed professionally, resulting in a low level of the tourism industry. Sensitivity analysis resulted in levels vary from “Low”/“Less Sensitive” to “Very High”/“Very Sensitive”.

ESI result for capture fisheries theme is influenced by the existence and usage of fishing gear by local fishermen. Passive fishing gear such as zero (guiding barrier), kelong (a combination of guiding barrier and fixed lift net) will be affected whenever the oil spill occurred. Whereas, active fishing gear such as gill nets and handline can be moved by fishermen away to avoid oil spills. Catch production of fish/shrimp commodities will be the main parameter of socio-economic value. The higher the economic value of fish/shrimp catches, the more sensitive the fishing area will be. During the period of April-September (dry season), according to the CESI method, the area with “Sensitive” level of sensitivity concentrated around four nautical miles from the coastline on the southern coast of Madura. Others area generally has “Moderate” and “Less Sensitive” insensitivity level. Whereas, based on IPIECA Method, the offshore area of the southern coast of Madura Island is generally categorized as “Very High” and “High” insensitivity level due to the existence of passive fishing gear used by local fishermen.

Human settlement both in the northern and southern coast of Madura Island is in the range of “Moderate”/“Medium” and “Sensitive”/“High” in the sensitivity levels. The agriculture field both on the northern and southern coast of the study area is in the range of “Moderate”/“Medium” in the sensitivity level.
The number of the area with a balance of sensitivity level between IPIECA and CESI method is the sensitivity level combinations of “Moderate”/“Medium” and “Sensitive”/“High”. No unit of analysis has an inconsistency level of sensitivity between IPIECA and the CESI method. It indicates that both the IPIECA and CESI methods tend to have corresponding results in the calculation of ESI.

According to management practices for implementation of the Oil Spill Contingency Plan (OSCP) program, it is possible to choose both IPIECA and CESI method. IPIECA method has a simple calculation of ESI analysis and may supply ESI maps instantly to prioritize the sensitive area against oil spill accidents. CESI method has adequate backbone coastal resources data and ready to be updated for managing the longtime sustainable coastal environments.

4. Conclusion
In general, the IPIECA’s class of sensitivity are higher than that of CESI’s on the following conditions: (1) natural ecosystems are found scattered almost throughout the study area even though the ecological data is not available, and (2) land use that produces more production output and involves many workers will have higher level of sensitivity.

CESI’s classes of sensitivity have a higher level than that of IPIECA’s whenever the IPIECA method demonstrates no consideration of the level of vulnerability of biota cultured against pollution (such as at fish/shrimp pond and mariculture).

The number of the area with a balance of sensitivity level between IPIECA and CESI is the sensitivity level combinations of “Moderate”/“Medium” and “Sensitive”/“High”.

Both IPIECA and CESI methods can be implemented on the Oil Spill Contingency Plan (OSCP) program. IPIECA method has a simple procedure to developed ESI Map while the CESI method requires complete environmental data. This environment data should be updated periodically for managing long time sustainable environmental management.

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