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Assessment of oil spill vulnerability of Southwest Pulau Pinang shoreline

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Abstract— The island of Pulau Pinang is located at the northeastern sector of the Straits of Malacca. Oil spill vulnerability assessment was carried out at the southwestern Pulau Pinang shoreline. The study includes field mapping, GIS mapping and analysis of the vulnerability of the shoreline resources in various geomorphic and land-use types. The study aims to assess the relative vulnerability of different types of shoreline and prioritising the shoreline types for protection following a large oil spill. The oil spill vulnerability index (VI) was prepared following the Environmental Sensitivity Index (ESI) approach of National Oceanic and Atmospheric Administration (NOAA) with adaptation to include shoreline types not listed under the ESIs. A modified oil spill vulnerability index (MVI) is formulated by taking into account the environmental and socio-economic value of the shorelines. The vulnerability index is increased by 3 ranks for shorelines with high environmental and/or socio-economic value, by 2 ranks for medium value and by 1 rank for low value.

The shoreline of southwest Pulau Pinang can be divided into nine natural and two units of man-made geomorphic units. The southern part of the shoreline is characterised by low to moderate oil spill vulnerability (MVI=1 to 6S), consisting mainly of exposed boulder beaches and exposed coarse sand beaches interspersed with lesser exposed cliffs and steep rocky shore, exposed mixed sand and gravel beaches and exposed fine sand beaches. In the north, the shoreline is highly vulnerable (MVI=8E to 10E), comprising largely of parallel strips of exposed tidal mudflat and mangrove.

Keywords: Oil spill vulnerability, environmental sensitivity index, coastal geomorphology, Pulau Pinang

INTRODUCTION

The Straits of Malacca is one of the most important trade route in the world. Each year more than 100,000 oil and cargo vessels traversed the Strait, carrying more than 3 million barrels of crude oil each day (Chua *et al*., 2000), exposing the water and shoreline of the Strait to constant threat of oil spill incidents. Although no major oil spill has occurred to-date, it is important to assess and analyse the shorelines along the Strait for their vulnerability to oil spill so that contingency plan or priorities for protection of various coastal ecosystems can be effectively set in an event of a large oil spill.

Gundlach & Hayes (1978) and Michel *et al*. (1978) proposed a rapid method to map and rank coastal environment in terms of their potential vulnerability to oil spill damage. The proposed Vulnerability Index classified coastal environments on a scale from 1 (least vulnerable) to 10 (most vulnerable) based on shoreline interaction with the physical processes controlling oil deposition, observed persistence of the oil in that environment and the extent of biological damage. The method has been refined and expanded to cover the estuarine, lacustrine, riverine, and palustrine environments by the National Oceanic and Atmospheric Administration (NOAA, 1995, 2002). The Environmental Sensitivity Index (ESI) of NOAA is the standard approach for the determination of shoreline sensitivity to oil spill in the USA and it is widely used worldwide (Masaki *et al*., 2001, Adler & Inbar, 2007), including Malaysia (Mohamad Nor *et al*., 2000).

Oil spill contingency planning requires information from several key components, including oil spill vulnerability maps, spill trajectories and equipment inventory, ideally integrated within a Geographical Information System (GIS) application. The trajectory model simulates the processes of spreading, advection, turbulent diffusion, evaporation and dissolution of an oil slick on the water surface (Chao *et al*., 2001). The location, time and volume of oil spill landfall are predicted using trajectory models from data such as location, time and estimated volume of the spill, the properties of the oil, the velocities and directions of winds and currents, air and water temperatures, tides and bathymetry (e.g. Barker & Galt, 2000; Copeland & Wee, 2006; Vethamony *et al*., 2007, Wanga *et al*., 2008). Once the expected landfall locations are identified, areas to be protected or cleaned can be prioritized by referring to the vulnerability index of the shoreline indicated on the oil spill vulnerability map and the equipment and personnel available for the operation.

This paper presents the results of oil spill vulnerability mapping and describes the enhancement of the ESI mapping approach by using the levels environmental and socio-economic sensitivities of the shorelines to modify the oil spill vulnerability index. The southwestern Pulau Pinang, which is located at the northeastern sector of the Straits of Malacca is chosen in this study.

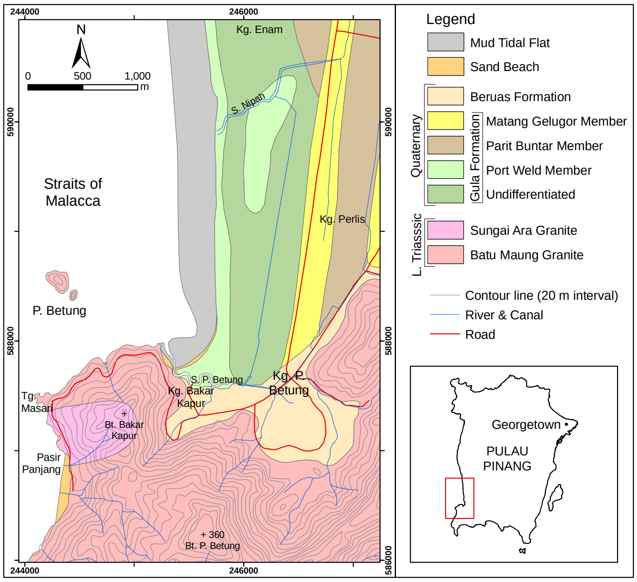

Figure 1: Geological map of the study area in southwest Pulau Pinang (modified after GSD, 1992 and Ong, 1993).

SETTING OF THE STUDY AREA

The shoreline of the Straits of Malacca at southwest Pulau Pinang between the West Malaysian RSO Northing 586,000 and 591,000 mE together with the shoreline of Betung Island was mapped. Although the shoreline is only 6 km long, it consists of a variety of geomorphic units and sedimentological units. The southern part of the area is underlain by granite bedrock and the shoreline is mainly rocky with lesser sand beaches (Figure 1). The northern part is underlain by Quaternary deposits comprising of Gula Formation and Beruas Formation (Kamaludin Hasan, 1990; GSD, 1992) and the shoreline is dominated by tidal mud flat and mangrove.

The shoreline of eastern coast of Pulau Pinang is generally exposed to open sea. Apart from the headlands, shoreface is generally shallow and has low slope gradient. In the area studied, the 5 m bathymetry line lies about 3 km from the coast indicating an average slope of about 1:600. The fluctuation of sea water level for the area is the result of astronomical tides. The tides are mixed, predominantly semi-diurnal form. The tidal range is about 2 m and the highest astronomical tide is 3.1 m. The net longshore current direction and sediment transport is shouthwards (EPU, 1985; Tjia, 2001).

METHODS

Aerial photographs, satellite imageries, maps and bathymetric charts of the area were studied prior to the field mapping and relevant information was digitised to produce a 1:5,000 scale base map in the ArcGIS Geographic Information System (GIS). Detailed mapping was carried out by foot during two field visits in December 2006 and December 2007.

Observations on the geomorphic characteristics, exposure level, slope gradient, types of substrate and sediment, landuse, as well as socio-economic and environmental importance of the shoreline were made. The data was used to classify the shoreline into nine geomorphological units (Figure 2a and 2b). The oil spill vulnerability of the shoreline was classified using the ESI approach, however, modification was made so that the shoreline can be classified properly. The original term oil spill Vulnerability Index (VI) by Gundlach & Hayes (1978) was used instead of Environmental Sensitivity Index (ESI) because the former term better describes the intended purpose of this shoreline classification.

The oil spill vulnerability classification for natural shorelines and shorelines modified by human activities are listed in Table 1 and Table 2, respectively. The shorelines are classified based on the following factors:

1. Relative level of exposure to wave and tidal energy.
2. Type of substrate and/or sediment.
3. Slope of the shoreline.
4. Biological diversity and productivity.

The classification of the natural shorelines was modified from the ESI classification, where shorelines not found in Malaysia (eg. tundra cliff) are removed. Exposed rubble or boulder shores which is given the rank of 1 in the ESI, together with rocky shores is moved to the second rank in VI, because the exposed rubble shores are generally less steep (a broader zone will be affected) than the rock shores and oil trapped between and under the boulders is more difficult and require a longer time to be cleaned by natural wave actions. The characteristics of the natural shoreline types are summarised in Table 1 and detailed descriptions of the shorelines are presented by Gundlach & Hayes (1978) and NOAA (2002).

The suffix "A" is added to the VI ranks of man-made shoreline types to differentiate them from the natural shorelines. Exposed reclaimed shoreline, which is usually consisting of compacted soil, sand and rock fragments are added and given the rank of 4A, while protected reclaimed shoreline is given rank of 8A (Table 2). However, if the reclaimed materials are reworked by coastal processes to form shoreline similar to natural types, the classification of natural shorelines can be used. For example, many reclaimed shorelines in the eastern Pulau Pinang now have the characteristics of exposed fine sand beaches, and they should be classified as such. Artificial "shoreline" formed by floating permeable structures or stilted structures such floating fish farms and houses, and stilted buildings are common in many parts of Pulau Pinang. The permeable structures are formed by linking many solid blocks and oil can get between the blocks. These "shorelines" are given the rank of 7A.

In the ESI approach, the biological and human-use resources are recorded and mapped. However, the ESI ranking is not affected by the value of these resources, for example an exposed steep rocky shoreline will be given a rank of 1 even if it is a nesting and feeding ground for an

Table 1: Summary of the oil spill vulnerability index (VI) of the natural shorelines and their characteristics.

VI No.	Shoreline type	Exposure level	Substrate type	Sediment type	Slope gradient	Permeability	Sediment mobility	Oil penetration	Natural oil removal	Physical condition of shoreline	Accessibility	Cleanup ability
1	Exposed cliffs and steep rocky shores	High	Rock	Not applicable	Steep to vertical (>30°)	Impermeable	Immobile	Oil on surface only	Fast (within weeks)	Hard. Flat to uneven surfaces.	Poor, on foot only	Difficult for oil in deep crevices and under boulders
2	Exposed wave-cut platforms and boulder shores	High	Rock and sediment	Boulders. May have patches of finer sediments	Sub-horizontal to moderate (<30°)	Generally impermeable	Generally immobile	Oil on surface and between boulders	Fast (weeks to months)	Hard. Flat to uneven surfaces.	Poor, on foot only	Difficult for oil in deep crevices and under boulders
3	Fine- to medium-grained sand beaches	Medium	Sediment	Fine to medium grained sand	Sub-horizontal (<5°)	Low permeability	Low	Low (<10 cm), oil can be buried	Medium to fast (months)	Dense. Flat	Good, by vehicles and on foot	Easy to remove oiled sediments
4	Coarse-grained sand beaches	Medium	Sediment	Coarse grained sand	Gentle (5° - 15°)	Moderately permeable	High	Medium (<25 cm), oil can be buried rapidly	Medium to fast (months)	Loose. Flat	Moderate. Vehicle may mix oil into sand.	Difficult. May needs to remove large ammounts of sediment
5	Mixed sand and gravel beaches	Medium	Sediment	Sand and gravel	Gentle (8° - 15°)	Moderately to highly permeable	Generally low, high during storm	Medium to high (<50 cm)	Slow (months to years)	Loose. Flat to slightly uneven	Moderate. Vehicle may mix oil into sediment.	Difficult. May needs to remove large ammounts of sediment
6	Gravel beaches	Medium	Sediment	Gravel, cobble and pebble	Gentle to moderate (10°-20°)	Highly permeable	Mobile during storm only	High (<100 cm)	Slow (months to years)	Loose. Flat to slightly uneven	Moderate. Vehicle may mix oil into gravel.	Difficult. May need to clean gravels.
7	Exposed tidal flats	Medium	Sediment	Fine sand and/or mud	Sub-horizontal (<3°)	Permeable (sand), low permeability (mud)	Low	Oil on surface only (wet), low (dry)	Medium to fast (months)	Soft. Flat	Poor. Oil may mix into sediment	Difficult.
8	Sheltered rocky and rubble shores	Low	Rock and sediment	Boulders. May have patches of finer sediments	Moderate to steep (>15°)	Generally impermeable	Generally immobile	Oil on surface and between boulders	Slow (years)	Hard. Uneven surfaces.	Poor, on foot only	Difficult for oil in deep crevices and under boulders
9	Sheltered tidal flats	Low	Sediment	Mud and/or fine sand	Sub-horizontal (<3°)	Low permeability	Very low	Oil on surface only (wet), low (dry)	Slow (years)	Soft. Flat	Poor. Oil may mix into sediment	Difficult
10	Mangroves	Low	Sediment	Organic –rich mud.	Sub-horizontal (<5°)	Low permeability	Very low	Oil on surface only (wet), low (dry)	Very slow (years)	Soft. Flat. Vegetated	Poor. Vehicle will damage vegetation and mix oil into sediment	Very difficult to clean oiled vegetation and remove oiled sediments

Table 2: Oil spill vulnerability index (VI) of man-made shorelines.

VI No.	Man-made shoreline type	Description
1A	Exposed solid structures or seawall	Impermeable vertical to subvertical structure. Oil coats surfaces and enters crevices.
4A	Exposed reclamation material	Mixture of soil, sand and rock fragments used for reclamation. Compacted. Low to medium penetration of oil.
6A	Exposed riprap	Traps oil between riprap boulders cannot be completely flushed out.
7A	Exposed permeable floating or stilted structures	Oil coats on surfaces of structure and traps between floating blocks. Difficult to clean and maneuver between blocks and stilts
8A	Sheltered, solid structures, seawall, riprap, floating and stilted structures. Sheltered reclamation material	Oil coats surfaces of structures and traps between riprap boulders. Very slow natural removal of oil due to low energy setting.

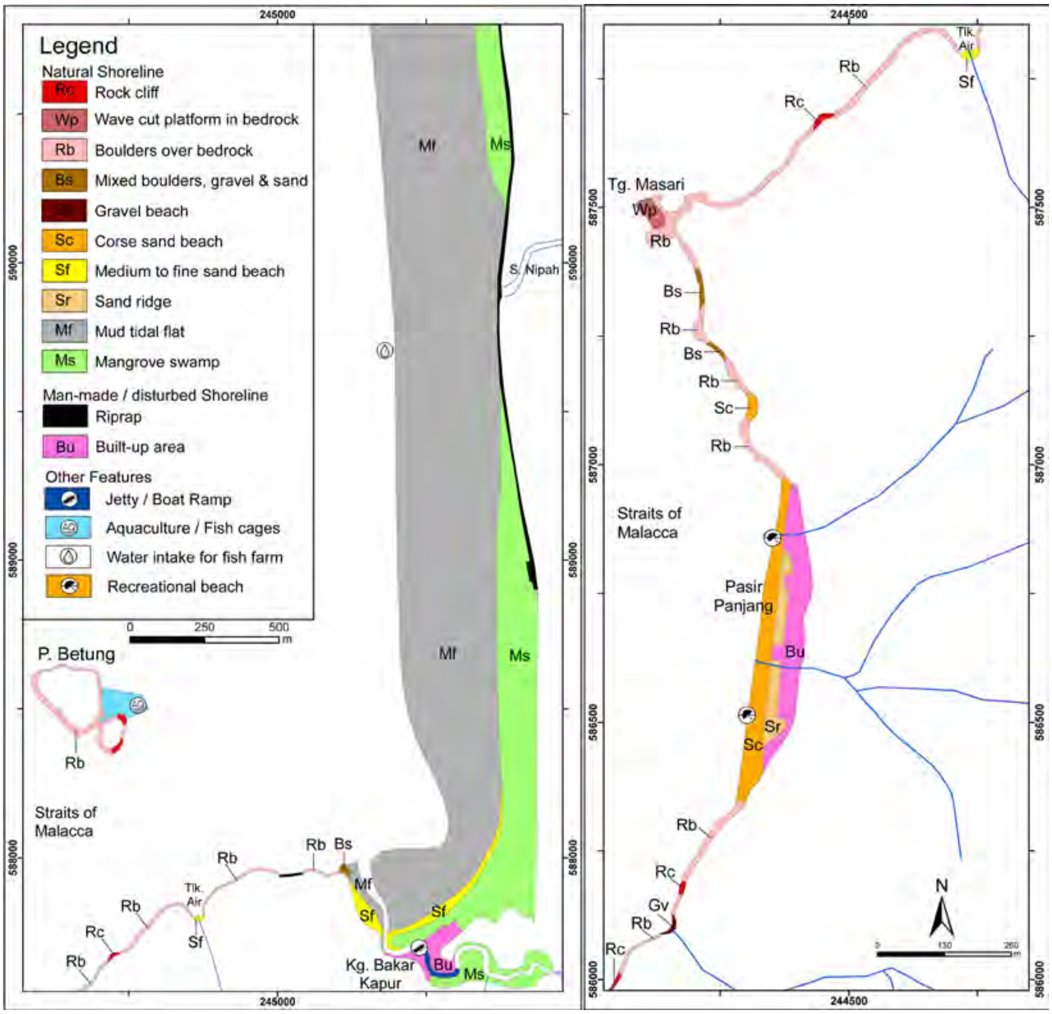

Figure 2: Shoreline geomorphology map of southwest Pulau Pinang.

Figure 3: a) The shoreline north of Kg. Bakar Kapur is consisting of three parallel units. They are exposed mud tidal flat (seawards, VI=7), exposed fine sand beach (VI=3) and mangrove (landwards, VI=10). b) The most common shoreline south of Kg. Bakar Kapur is consisting of boulders over bedrock (boulder shores, VI=2). c) Rock cliff at the southern end of the study area (VI=1). d) Wave cut platform at Tg. Masari (VI=2). e) Coarse sand beach at Pasir Panjang (VI=4). f) Mixed sand, gravel and boulders on the beach near Kg. Bakar Kapur (VI=5).

Table 3: Modified oil spill vulnerability index based on the environmental and socio-economic value of the shoreline.

Shoreline type	Base VI No.	Modified VI No.					
		ES-1	ES-2	ES-3	SE-1	SE-2	SE-3
Exposed cliffs and steep rocky shores	1, 1A	2E	3E	4E	2S	3S	4S
Exposed wave-cut platforms and boulder shores	2	3E	4E	5E	3S	4S	5S
Fine- to medium-grained sand beaches	3	4E	5E	6E	4S	5S	6S
Coarse-grained sand beaches	4, 4A	5E	6E	7E	5S	6S	7S
Mixed sand and gravel beaches	5	6E	7E	8E	6S	7S	8S
Gravel beaches	6, 6A	7E	8E	9E	7S	8S	9S
Exposed tidal flats	7, 7A	8E	9E	10E	8S	9S	10S
Sheltered rocky and rubble shores	8, 8A	9E	10E	10E	9S	10S	10S
Sheltered tidal flats	9	10E	10E	10E	10S	10S	10S
Mangroves	10	10E	10E	10E	10S	10S	10S

Table 4: Environmental value used to modify the oil spill vulnerability index.

Code	Environmental value	Description / Example
ES-3	High	Gazetted national parks, permanent forest reserves, marine parks and heritage sites. Area with endangered or threatened species.
ES-2	Medium	Areas with high biodiversity and/or biological productivity such as shallow coral reef and mangrove.
ES-1	Low	Areas with medium biodiversity and/or biological productivity such as sea grass and algae beds, cockle bed, migratory bird feeding ground.

Table 5: Socio-economic value used to modify the oil spill vulnerability index.

Code	Socio-economic value	Description / Example
SE-3	High	Highly used recreation areas. Military facilities. Water intake for power plant.
SE-2	Medium	Commercial ports. Marine aquaculture facilities. Shoreline assocaited with archeological, historical and cultural sites. Moderately used recreational areas. Commercial, industrial, institutional and residential areas and infrastructures which oil spill may affect their immediate activities or usage.
SE-1	Low	Lightly used recreational areas. Commercial, industrial and institutional areas which oil spill does not affect their immediate activities. Small local ports or jetties.

endangered bird species, within a national park. In order to better represent the actual vulnerability that encompasses the environmental and socio-economic sensitivities of the shorelines, a modified oil spill vulnerability index (MVI) is used. The environmental and socio-economic sensitivities or values are used to modify the base VI ranking of the shorelines (Table 3). A suffix "E" to denote ranking increased due to environmental value, and a suffix "S" is for increase based on socio-economic value. If both the environmental and socio-economic values are negligible, the VI is not changed (MVI = VI), and no suffix is placed after the MVI rank. If both the environmental and socio-economic values are present, the one that has the higher value or importance will be used. The vulnerability index is increased by 3 ranks for shorelines with high environmental and/or socio-economic value (ie. MVI=VI+3), by 2 ranks for medium value and by 1 rank for low value.

The environmental value is ranked as high (ENV3) for shorelines within gazetted national parks, permanent forest reserves, marine parks and heritage sites, as well as where endangered or threatened species are present (Table 4). Other shorelines with high biodiversity and/or biological productivity is considered as having medium environmental value (ENV2), while shorelines with medium biodiversity and/or biological productivity is considered as having low environmental value (ENV1). Shorelines with low biodiversity and/or biological productivity are deemed as having negligible environmental value.

In term of socio-economic value, shorelines highly used for recreation, military facilities and water intake for power plants are considered as highly sensitive (SEV3, Table 5). Ports, marine aquaculture facilities, shorelines associated with archaeological, historical and cultural sites, moderately used recreational areas as well as commercial, industrial, institutional and residential areas and infrastructures are given medium socio-economic value (SEV2). Low value (SEV1) is considered for lightly used recreational areas and commercial, industrial and institutional areas which oil

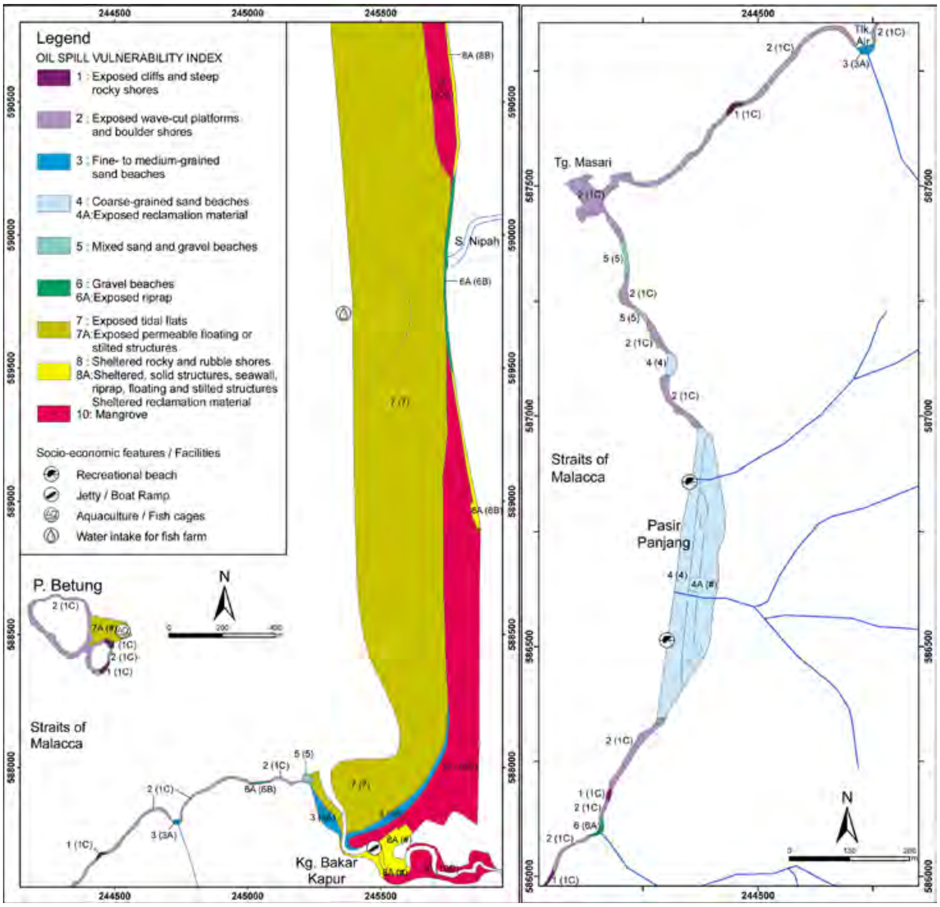

Figure 4: Oil spill vulnerability map of southwest Pulau Pinang.

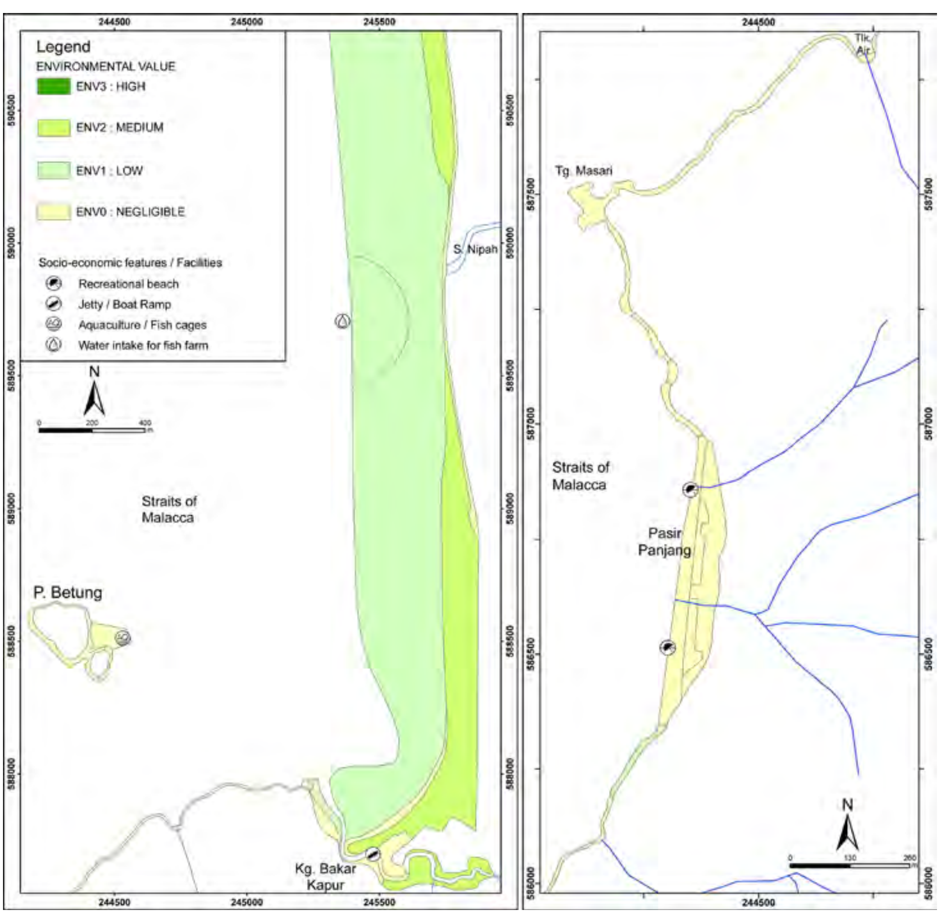

Figure 5: Map showing the environmental value of the shorelines of southwest Pulau Pinang.

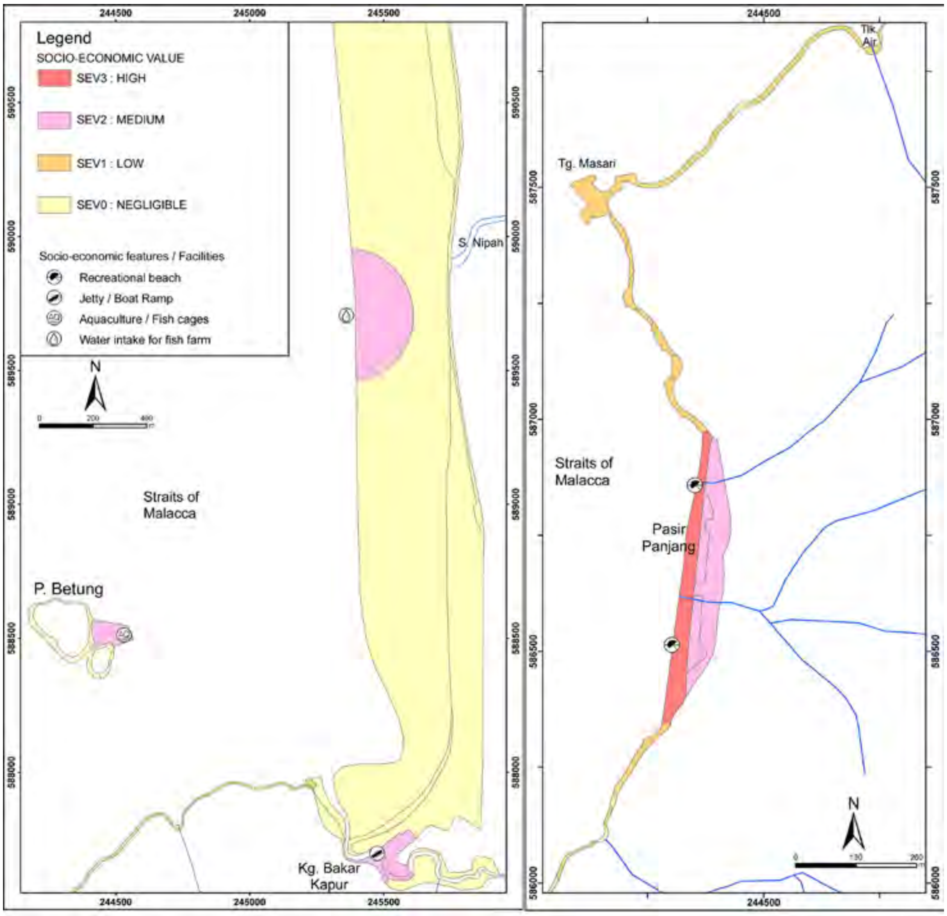

Figure 6: Map showing the socio-economic value of the shorelines of southwest Pulau Pinang.

spill will not affect their immediate activities. Shorelines with no economic use and no archaeological, historical and cultural significance are considered as having negligible socio-economic value.

RESULTS

The geomorphological mapping results in the identification of ten natural and two disturbed or man-made geomorphic units (Figure 2). The shoreline north of Kg. Bakar Kapur is characterised by a tidal mud flat of about 300 m wide and occurring as a north-south trending strip. Eastwards, further from the waterline, there is a narrow strip of mangrove. The mangrove is about 100 m wide but tapers and diminishes towards S. Nipah estuary. North of Kg. Bakar Kapur, there is a narrow strip of fine sand beach separating the mud flat and the mangrove (Figure 3a). At Kg. Bakar Kapur, the mangrove area has been reclaimed. The mangrove is usually above water level and it is exposed to the waves mainly during spring high tides and storms.

The shorelines of the rest of the study area, including those at Pulau Betung are mainly rocky and consisting mainly of boulders over bedrock, mixed boulder, gravel and sand, and rock cliff (Figures 2, 3b, 3c and 3d). These shorelines are relatively narrow and irregular. There is a straight coarse sand beach at Pasir Panjang, which is 1.25 km long and about 100 m wide. There are also two small pocket beaches, one located about 150 m north of Pasir Panjang that is consisting of coarse sand, and the other at Teluk Air is consisting of medium to fine sand.

Due to the presence of more than one geomorphic unit along the shoreline, the oil spill vulnerability map north of Kg. Bakar Kapur is characterised by two to three parallel strips with different vulnerability index (Figure 4). The shoreline near Kg. Bakar Kapur is consisting of exposed tidal mud flat (VI=7), followed by a narrow strip of exposed fine sand beach (VI=3) and mangrove (VI=10) (Figure 3a). The mud flat and fine sand beach are exposed during normal condition and the landward facing mangrove is exposed to oil mainly during spring high tides, surging waves and storms. Further north is consisting two units: tidal mud flat (VI=7) and mangrove (VI=10), and followed by an additional strip of riprap sheltered by the mangrove (VI=8A). Near the estuary of S. Nipah, the riprap is exposed (VI=6A).

The shorelines west and south of Kg. Bakar Kapur and at Pulau Betung are consisting mainly of one narrow geomorphic unit that is characterised by exposed boulder beaches (VI=2, Figure 3b) and exposed coarse sand beaches (VI=4, Figure 3e). There are lesser exposed cliffs and steep rocky shore (VI=1), exposed mixed sand and gravel beaches (VI=5, Figure 3f) and exposed fine sand beaches (VI=3) occurring in short stretches between the boulder beaches.

For the modified oil spill vulnerability index classification, the mangrove is considered as having medium

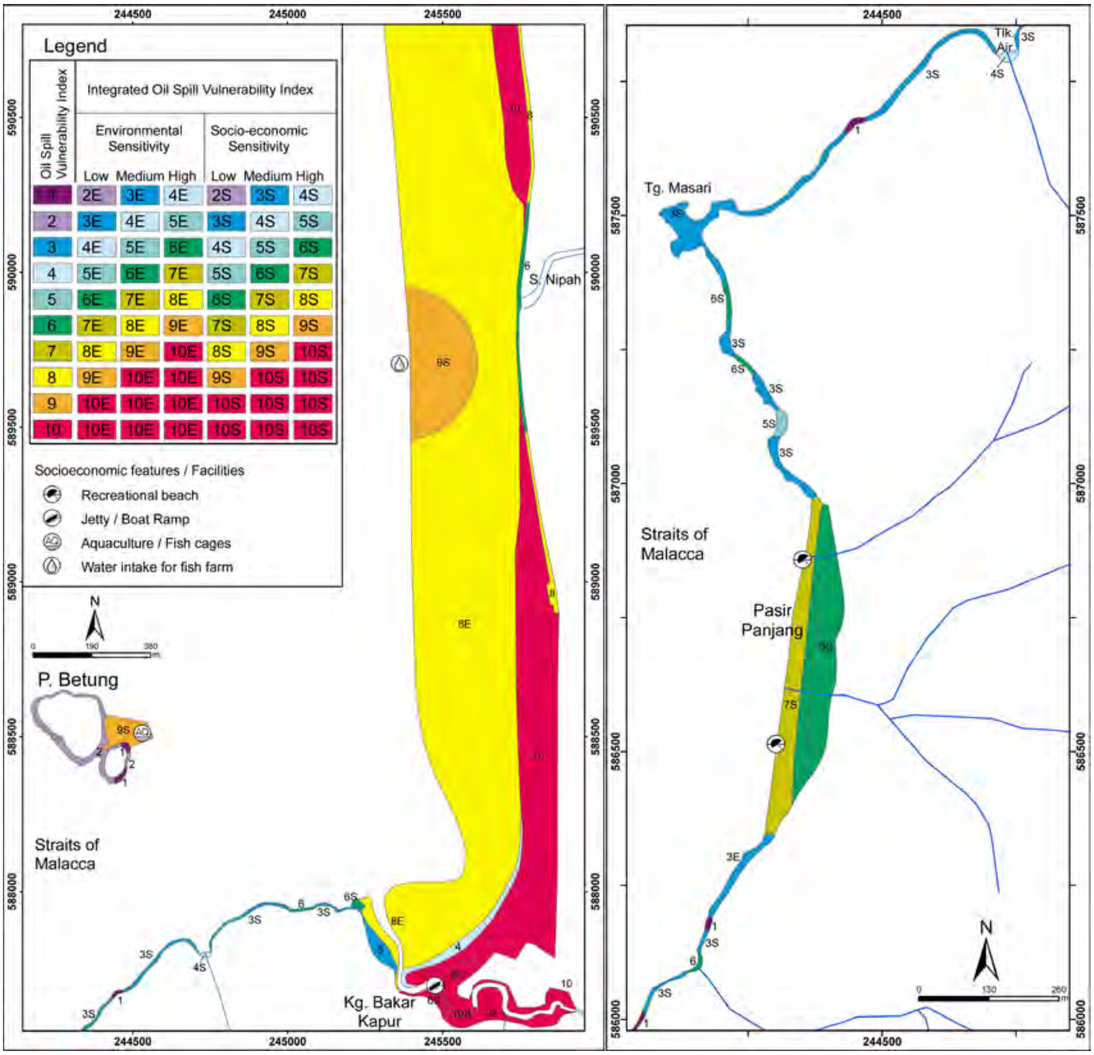

Figure 7: Map showing the modified oil spill vulnerability by taking into consideration the environmental and socio-economic values of the shorelines.

sensitivity (ENV2). However, the MVI rank remains the same (10E) because the mangrove already has the highest VI rank. The tidal mud flat with abundant infauna and is a feeding ground for shore birds, and the rocky beach south of Pasir Panjang with abundant macro-algae is considered as having low sensitivity (ENV1), giving MVI values of 8E and 3E respectively (Figure 5).

The moderately used popular beach at Pasir Panjang (MVI=6S) is considered as having moderate socio-economic value (SEV2, Figure 6). Medium socio-economic sensitivity is also assigned for the village of Kg. Bakar Kapur (MVI=10S; for part of the village that can be exposed to oil during spring high tide and storm), the jetty and fishing boat ramp in the same village (MVI=10S), the institutional area east of the Pasir Panjang beach (MVI=6S), the tidal flat areas within 250 m from a water intake for an aquaculture facility near S. Nipah (MVI=9S), and the floating fish cages at P. Betung (MVI=9S). Apart from the steep rock cliffs that has negligible socio-economic value, the rocky and sandy coastlines are lightly used for recreational fishing and are given low socio-economic weightage (SEV1).

DISCUSSION AND CONCLUSION

Mapping and analysis of the oil spill vulnerability using the ESI method (with modification described above) of the Southwest Pulau Pinang coastlines using GIS provide an important component for an effective contigency planning system for the prioritisation of shoreline protection in an event of a large oil spill. A modified oil spill vulnerability index (MVI) is formulated where environmental and socio-economic values of the coastline are integrated into the vulnerability analysis to provide a better representation of the overall vulnerability.

The coastline north of Kg. Bakar Kapur, which is consisting mainly of exposed tidal mud and mangrove has high vulnerability to oil spill (MVI = 8E to 10E, Figure 7). The rest of the coastline is consisting of exposed boulder beaches, an exposed coarse sand beach at Pasir Panjang and lesser short stretches of rock cliffs and beaches with fine to medium sand, mixed sand and gravel, and gravel. These shorelines have low to moderate oil spill vulnerability (MVI=1 to 6S, Figure 7).

Several sub-parallel shoreline types with different oil spill vulnerabilities are present at Pasir Panjang and north of Kg. Bakar Kapur. The seaward strip is exposed to potential oil spill most of the time during "normal" tidal conditions and calm sea and the landward strip is exposed to oil mainly during spring high tides, surging waves and storms. This does not mean that the landward strip has lower potential for oil spill incidences because many oil spill incidences occur during bad weather.

For the management of the coastline in the regional scale, it is desirable to aggregate or collapse the multiple shorelines types in the same location into a single priority target. The short shoreline units will also need to be combined in the regional map. Several approaches can be used in the data aggregation. One can use the highest MVI rank, or identify and use the MVI rank of the shoreline unit with highest environmental and/or socio-economic value, or lastly, use the MVI rank of the dominant shoreline unit. The approaches chosen should take into consideration the purpose and targets of protection.

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