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Review on Marine Oil Spill Trajectory Modeling and ESI Mapping with a focus on the Kerala Coastal Environment.

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Abstract: - *This report addresses marine oil spill trajectory modeling and Environmental severity Index mapping with a focus on the Kerala coastal environment. With growing Indian demand for the crude oil the Kerala coastal area will be exposed to increasing risk of oil spills from marine transport. Oil spill trajectory models are an essential tool for risk assessment related to potential environmental impacts in sensitive areas for Kerala coast and for planning spill response measures. This study is a review of the oil spill modeling literature, special emphasis was given to the physical, biological and ecological coastal area of Kerala having 590Km of coastal line. The first goal is a synthesis of the oil spill trajectory modeling and its various components. The second goal is the identification of the most vulnerable areas to oil spill in the coastal belts of Kerala. A comprehensive oil spill trajectory model for the Kerala coastal area would include: 1) Models for the physical environment (Wind, air temperature, precipitation, ocean currents, and waves), 2) An oil spill model to address weathering, evaporation, and other details of the oil's interplay with the marine environment.*

***Index Terms*: -** *Environmental severity Index mapping, Kerala coastal environment, Oil spill, Trajectory modeling.*

I. INTRODUCTION

The growth of the oil transportation and macro-scale operations technology of the oil tanker will increase the possibility of cargo oil contamination especially large oil contamination incidents along the coast of Kerala in the future. In recent years there has been a growing concern over the increasing contamination of water bodies and adjacent shoreline areas by oil spills. Some processes, such as industrial discharge, oil exploration and transport, oil storage facilities, etc., have increased the risk of oil spill accidents. The oil spill accident is very harmful to the ocean environment and the health of mankind. A major oil spill can contaminate the shoreline, cause long-term damage to the aquatic environment for fishery and human life [1]. Oil spills may also foul the harbor facilities and vessels. To prepare for such accidents, many government agencies have prepared oil spill contingency plans. An important component of these plans is the use of mathematical models to predict the oil slick motion and distribution of oil particle concentrations in the coastal waters. Generally, the physical, chemical and biological processes can affect the transport and fate of spilled oil. These include spreading, advection, evaporation, dissolution, emulsification, photo-oxidation, sedimentation, and biodegradation [2]. The chemical and biological processes generally occur a long time after the oil spill. Under the actions of the breaking wave and upper layer turbulence, the oil slick will break up and become small particles, then advect and diffuse in the water column. Some of the particles will resurface, while some will form water-in-oil or oil-in water emulsions. The specific gravity of the resulting emulsion oil is close to the water [3]. The oil particles can stay in the water column for a long time, and pollute the coastal water environment.

The three dominant processes that cause changes in oil characteristics over time are spreading, evaporation and emulsification if oil spills at sea. Spreading reduces oil thickness, and evaporation increases density and viscosity. The emulsification process significantly increases the viscosity of spilled oil and its density [4]. Oil spill accidents such as Erika in France (1999) and Prestige in Spain (2002) have highlighted the importance of developing new tools to support spill response planning. In order to respond rapidly and successfully to an oil spill, a contingency plan including information and processes for oil spill containment and clean-up is required. A fundamental part of these plans is the determination of which coastal environments would be most seriously damaged by an oil spill so that they may receive priority protection [5]. Environmental Sensitivity Index (ESI) mapping provide a concise summary of coastal resources that are at risk if an oil spill occurs nearby. For this identify the most vulnerable areas to the oil spill in the coastal line of Kerala using the stimulated fate and trajectory of oil slick. For this the risk resources include biological resources (such as birds and shellfish beds), sensitive shorelines (such as marshes and tidal flats), and human-use resources (such as public beaches and parks) are to analysed.

Oil spills have the potential to cause serious harm to the marine environment in which they occur. They are capable of causing widespread economic and environmental damage [6]. This study enumerate the risks of oil spills in coastal area of Kerala and identify the vulnerable areas of oil spill. This will help to develop methods to combat the spill that would be invaluable in minimizing the extent to which oil can devastate the ecosystem in Kerala coastal area.

II. OIL SPILL PROCESSES

When oil is spilled into a marine environment, it is subject to several processes including spreading, drifting, evaporation, dissolution, photolysis, biodegradation and formation of water–oil emulsions [2]. When oil spills on water, various transformation processes occur that are referred to as the “behaviour” of the oil. In this two types of transformation processes are discussed. The first is weathering, with emphasis on evaporation, the formation of water-in-oil emulsions, and natural dispersion, and the second is a group of processes related to the movement of oil in the [7]environment.

Spreading on the water surface –

Spreading is the horizontal expansion of an oil slick due to gravity, inertia, viscous and surface tension forces. While spreading an oil slick considered to pass through three phases and the axi-symmetrical spreading diameter in each of the phases can be defined by Fay [8], influence of wind not consider. Lehr, et al. [9] formulated a modified Fay-type spreading equation considering the influence of wind. Based on the Lehr formula, the area of the oil slick due to spreading at every time step can be obtained.

Advection and turbulent diffusion on the water surface –

The shape and track of the oil slick are very important for predicting the oil movement. Xiaobo, et al. [10] developed a 2-D oil spill model, in which the initial oil slick area is divided into a number of small grids, and a set of plane coordinates are assigned to each grid. It is assumed that these grids advect with the surrounding water body and diffuse as a result of random processes. Based on the flow fields on the water surface and the wind velocity, the advection and diffusion properties of each grid point was calculated. Then the velocity and displacement of each grid can be solved. After calculating the grid coordinates at every time step, the shape and track of the oil slick can be decided. The advective velocity of each grid point computed from the surface water current velocity, current factor and wind velocity using the 3-D turbulence tidal model [11]. The diffusive velocity component can be modeled by a homogeneous random walk model based on Al-Rabeh, et al.’s study [12].

Evaporation –

Shortly after an oil spill (hours to days), evaporation is the most important weathering process and causes changes in chemical composition and physical properties of the oil (boiling point, density, viscosity). The rate of evaporation is largely governed by the chemical properties (i.e. vapor pressure) of the constituents and, to a lesser degree, by boundary layer saturation [13]. Mackay [14] developed a multi component theory to compute the rate of oil evaporation.

Vertical dispersion –

The oil slick on the ocean is also subject to the action of waves, especially breaking waves and upper layer turbulence. Under their actions, the coherent oil slick will break up and become small particles, then advect and diffuse in the water column. Delvigne and Sweeney [15] described the entrainment rate, particle size and intrusion depth of oil particles as a function of the oil type, breaking-wave energy and temperature using empirical relations.

Emulsification –

Mark Reed, et al. [16] developed a three-dimensional trajectory model and tested against data from experimental oil spills at sea. Observations suggest that emulsified surface oil will drift down wind at speeds in excess of 3% of the wind speed.

Shoreline deposition –

Oil may be brought to and deposited along the shoreline, and re-entrained into the water. Field observations of large spills indicate that the capability of beaches to hold oil is limited. Once the shoreline capacity is reached, oil will be exposed to long shore transport processes. Humphrey et al. [17] calculated the maximum capacity of beach for oil. Small amounts of oil that can persist for decades in the inter tidal zone of coarse-sediment beaches have been documented by Edward, et al. [18].

III. OIL SPILL FATE MODELS

Crude oil contains plenty of different ingredients and every ingredient has different steam pressure, dissolvability, viscosity and surface tension [1]. The group of high volatility evaporates very quickly, while the group of light carbon dissolves gradually in water, and the group that does not easily volatilize is left on the sea. Zhao and Wang [19] studied the behavior of the oil slick on the water surface in the Huangpu River, a tidal waterway in Shanghai based on particle approach and tidal flow model. In order to track the oil slick motion, a two-dimensional oil trajectory model is used. The dynamical properties of spilled oil characterized by advection, oil spreading and turbulent diffusion are considered in the model. The calculated results can be used as a reference for the response to oil spill accidents in rivers.

Particle approach - Chen, et al. [1] developed a mathematical model of oil spill on the sea with the consideration of spread, diffusion, drifting and attenuation of oil slick is influenced by evaporation and emulsification factors. A model that under the effect of ocean dynamic condition of tide, wind and wave, using Monte Carlo method to simulate the movement of oil slick is established. The modeling is applied to calculate and predict pollution range of oil spill at oil quay and oil ship in Daya Bay. The prediction results have basically shown the pollution situation by emergency of oil spill on the sea.

Numerical model of continuous spill drift - For continuous spill, we use the method of tracing boundary particles to determine the actual shape of slick, taking into consideration the combination of original oil slick and the new oil spill slick, and also the effect of evaporation, emulsification, attenuation and swelling along the seaside sorption, Castanedo, et al. [20] developed a model based on the analysis of a database of hypothetical oil spill scenarios simulated by means of a Lagrangian transport model. In this analysis, the probability that a given oil spill will reach a specific receptor site was calculated over a different number of scenarios. In this study for a given oil spill the probability of the oil reaching the receptor sites located on the Cantabrian coast 30 days after its release was calculated.

Two-dimensional oil spill model for surface oil slick - Xiaobo and et al.[11] presents the development and application of two-dimensional and three-dimensional oil trajectory and fate models for coastal waters. In the two dimensional model, the oil slick is divided into a number of small grids and the properties of each grid due to spreading, advection, turbulent diffusion, evaporation and dissolution are studied.

Three-dimensional fate model for oil particle concentration - A 3-D multi-level tidal hydrodynamics model has been developed based on the 3-D Navier–Stokes equations [11]. Drozdowski, et al. [21] developed a comprehensive marine oil spill trajectory model for the Canadian Arctic ,which would include: 1) A blowout plume model to determine the distribution of the oil in the water column for spills occurring at depth. 2) Models for the physical environment (Wind, air temperature, precipitation, ocean currents, sea ice and waves) 3) An oil spill model to address weathering, evaporation, ice-oil interactions, and other details of the oil's interplay with the environment.

IV. SPILL RESPONSE

One of the most visible and most important cases of marine pollution is the oil pollution caused both accidentally and by routine ship operations. The objective of all oil spill response strategies should be to minimise the damage, both ecological and economic, that could be caused by an oil spill. The most obvious way to do this is to prevent the spilled oil from coming into contact with oil-sensitive resources. Most damage is done by spilled oil when it gets into shallow water or comes ashore. The objective of oil spill response actions at sea should be to prevent oil from reaching the shoreline or particularly sensitive resources at sea, such as fish spawning grounds [22]. The response actions can include:

1. Using booms to contain the oil near the spill source
2. Using sorbents to soak up the oil near the spill source.
3. Using booms and skimmers to contain and recover the oil at sea, before the oil drifts too close to the shore.
4. Using booms to protect a shoreline resource and divert the spilled oil away from it.
5. The in-situ burning, the bioremediation.
6. Using oil spill dispersants to disperse the oil into the water column before it approaches an oil-sensitive site.

All of these techniques have certain capabilities, but all suffer from limitations.

V. VULNERABILITY MAPPING

The concept of vulnerability is used in several definitions of risk. The United Nations, through the International Strategy for Disaster Reduction, defines risk as "the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions" [23]. It has adopted the classical convention expressed by the notation:

$$\text{risk} = \text{hazard} \times \text{vulnerability}.$$

The United Nations, through the International Strategy for Disaster Reduction, defined vulnerability as "the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards" [23]. Schmidtlein, et al. [24] defined vulnerability as "the likelihood of sustaining losses from some actual or potential hazard event, as well as the ability to recover from those losses." This definition stresses the importance of resilience. According to Ania Mentoza, et al. [25] the three types of variables chosen for vulnerability study were related to physical, biological and socio-economic criteria. For the physical criteria the focus was set on those land features that influence the water dynamic, that facilitate crude oil dispersion and penetration and that complicate oil spill cleaning actions. For the biological conditions a protection focus was adopted, and the main factors were ecological value and ecosystem integrity. Finally, the socio-economical conditions were those that allow the assessment of the potential damage to human health. Three of the main general characteristics recognized to establish a general view of the biological situation of a region are: richness, singularity and integrity [26]. Richness as the amount of different species that live in a region; singularity as the number of rare or endangered species homed in it, and integrity as an index to establish the amount of perturbation destruction of the original ecosystems. Identification of vulnerable areas by the analytical hierarchical procedure. A scale of five vulnerability levels (very high (I), high (II), medium(III), low (IV) and very low (V)) was adopted.

The vulnerability mapping of the potential risks is one of the key attributes of effective response and management of oil spill response planning. Vulnerability assessment is defined by "the extent of injury and damage that may result from a hazard event of a given intensity in a given area. The vulnerability assessment should address impacts of hazard events on the existing and future built environment" [27]. The threat of crude oil spills is greatest in those regions with a high concentration of oil extraction and refining activities. Ania, et al. [28] ranked the geosystems of the Coatzacoalcos and Tonalá Rivers basin of Mexico in terms of vulnerability to pipeline crude oil spills. Very high vulnerability (level I) was assigned to the water bodies (lakes and rivers) and their margins of influence, including surfaces that flood during normal hydraulic load. High vulnerability areas (level II) comprised surfaces that can flood during extraordinary hydraulic load related with extreme hydro meteorological events. The remaining three vulnerability levels were defined for areas with low or negligible flooding potential. Vulnerable levels were ranked according to physical (slope, relief and permeability), biological (richness, singularity and integrity) and socio-economic (social marginalization index and economic activities index) conditions. These results are presented on a map for better visualization and interpretation. This study will be useful to establish preventive and effective emergency management actions in order to reduce remediation costs and adverse effects on wild species. It also can help local and national authorities, oil industry and civil protection corps to better protect ecosystems, natural resources and human activities and goods. Feng Yu and Yong Yin [29] studied the spread, drift, evaporation and emulsification models of an imaginary oil spill happened in a stationary position in the sea. For the research situation of oil spill visualization, Feng Yu and Yong Yin[29] uses the techniques of planar refraction map and texture rendering to realize the 3D visualization of oil spill on the sea, and then designs a collision detection algorithm between oil and island, finally realizes the simulation and 3D visualization of oil moving around an island. A 2D model is adopted to simulate tidal current of island waters. The simulation results show the rendering speed is fast, the rendering effects are satisfactory.

Coastal sensitive areas mapping - The 700 km coastline of Kerala is endowed with a number of natural resources and beauty. Several rivers flowing to meet the arabian sea and form the wide extensive estuaries. Besides, Kerala is land of Beaches and back waters, scattered all along the coastline, which are populated by tourist around the year. All these are face the risk of irrevocable damage in case of any oil pollution affecting them. A Major spill could affect several areas around the coast making it desirable to coordinate activities amongst a number of Agencies. The pollution from , collision, stranding, and other Marine accidents can threaten marine life in the inter-tidal Zones, fisheries, sea birds, recreational beaches and tourism.

Environmental Impact - Fingas Mervin [7] reviews the many and varied effects of oil on different elements of the environment and summarizes the state of the art in assessing the damage caused by oil spills. The effects of oil on various organisms in the sea are discussed, as well as effects on freshwater systems, life on land, and the effects of oil spills on birds. Oil can have a significant impact on marine larvae, birds and mammals in particular, and to a lesser extent on fish. Some components of oil are toxic if exposure occurs within the first two days of a spill (1 part per million [ppm], i.e. one gallon in one million gallons, can be toxic to invertebrate larvae; 1000 ppm for fish). Oil on feathers hinders the water-repellancy of the bird. Oil on fur takes away its insulating capacities.

Karina, et al. [30] developed an oil spill-food chain interaction model, composed of a multiphase oil spill model (MOSM) and a food chain model, to assess the probable impacts of oil spills on several key marine organisms (phytoplankton, zooplankton, small fish, large fish and benthic invertebrates). The MOSM predicts oil slick thickness on the water surface; dissolved, emulsified and particulate oil concentrations in the water column; and dissolved and particulate oil concentrations in bed sediments. Jordi, et al. [31] describe a hybrid ocean forecasting system to predict oil spill trajectories and their potential impacts on the coastal zone.

VI. CONCLUSION

Accidental spills of oil can deposit very large volumes into the sea over a short period of time and in a comparatively localised area. This can cause temporary ecological damage, although natural recovery will eventually occur. The physical effects of the spilled oil, plus the less visible effects caused high concentrations of toxic components released from the oil, will affect the some marine resources in a localised area. The dead and dying seabirds covered in thick, sticky oil have become the 'icon' of oil pollution in the last decades [22].

Shorelines affected by oil spills go through a predictable sequence of affects; dead and dying crabs, lobsters and shellfish will be washed ashore if crude oil or diesel fuel is spilled. On rocky shores, many limpets will become detached from the rocks and gulls will feast on them. Nature will recover after even the worst oil spills; it may take up to 20 or 30 years or longer in particularly sensitive areas, but eventually almost all of the affected habitats will be as biodiversity and as productive as they were before the oil spill. A large oil spill can cause extensive disruption to the activities of many people in coastal communities. Feelings can run very high. Many people will feel that their local community has been ruined by the negligence or carelessness of outsiders. A shoreline heavily polluted with oiled seaweed and dead and dying creatures are a distressing sight. It can take some time and a lot of effort to clean it up. The perception is that a catastrophe has occurred, despite the fact that oil spills are rarely the 'environmental disasters' that the press confidently predicts on each occasion. The reputation of the oil and shipping industries will suffer when oil spills occur. Effective oil spill response must be reasoned and rational and carried out with urgency.

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