

Role of Geophysical Models in Environmental Disaster Management

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Abstract

The present paper is a report of strategic schemes to improve the disaster management advisories for nuclear power plants in India. The response to natural disasters and man-made accidents are treated separately and we provide a methodology for implementing them. Since natural disturbances are fairly predictable a few days in advance, a proper real-time simulation of the atmospheric and oceanic dispersion of the effluents with a good scheme to disseminate the information to general public (through NKN networks) will help in reducing the inconvenience to the people. Seasonal and monsoonal variations in currents, waves and winds will determine where and how far the effluents travel. On the other-hand, man-made errors and accidents being quite unpredictable, a better action plan can be drawn up using a vulnerability ma. We propose that, the vulnerability analysis should be done with the aid of Particle Trajectory Tracking Models (PTTM).

Keywords: Real-time simulations; Effluents; NKN network; PTTM

Introduction

After the fossil fuel free energy sources have come into use (mainly due to the climate change implications), large amount of electricity is being produced through nuclear power plants. We can find most of such power plants next to water bodies because of the requirement of cooling water for the nuclear plant operations. This is true even though they produce a lot of thermal and chemical waste. Since some of these chemical effluents are toxic to ecology and human health, it is important to study the fate of these nuclear wastes after they are discharged into the ocean. A leakage of such toxic waste can be extremely harmful, as is attested by the Chernobyl disaster and recent explosions near the Fukushima power plant. A numerical study of thermal plume discharge in the ocean is very important in the context of nuclear power plants. Thermal contamination is a major problem occurring in many coastal ecosystems caused by nuclear power plants [1]. Grassl [2] pointed out that SST is an important aspect for spatio-temporal variability of the thermal pattern in coastal waters. It helps one to understand the influence of thermal water on marine ecology and human life along the coastal regions. Such studies are useful for the implementation of new industrial units along coastal regions.

As part of the studies to follow effluents in ocean, one can find an ensemble of models used to understand the physical processes of a coastal oceanic system. The success rates for these ensemble models have gained them substantial attention and popularity among the scientific community. Among these, the role of ocean and atmospheric models in studying coastal processes has been reported by several authors and the highlights of the work done by a few authors with regards to coastal monitoring is mentioned below.

A lot of previous work has been done on atmospheric models. Srinivas et al. [3,4] conducted several numerical simulations to understand the effect of nuclear pollutants in the atmosphere designed for hypothetical accidental scenarios. There have been studies conducted to understand the role of atmospheric parameters on

thermal waters at the outfall region to trace nuclear effluents at Kalpakkam region. Therefore, it is important to understand the role of atmospheric parameters in the dispersion of thermal water from the outfall source and the trajectory of nuclear effluents in the vicinity of nuclear plant. In the context of coastal Kalpakkam along Chennai coast, an advanced two-dimensional depth-integrated finite element (ADCIRC) model was used by Rao et al. [5] to understand the coastal circulation features, storm surge and associated water levels. Their study highlights that potential inundation can occur when pressure deficit exceeds a threshold value of 66 hPa and horizontal extent of inundation can range between 1 to 1.5 Km associated with peak surge. In another study for the same region, Bhaskaran et al. [6] investigated the performance and validation of a coupled parallel ADCIRC-SWAN model for Thane cyclone that had landfall between Cuddalore and Pondicherry. An extensive validation experiment was performed Bhaskaran et al. [6] for the significant wave height and surface currents with in-situ, satellite and HF Radar observations. Bonthu et al. [7] applied a flux coupler mechanism to develop a regional coupled atmosphere-ocean modeling system for coastal Kalpakkam. This was used to study coastal circulation and the effect of thermal plume discharge from the nuclear plant on coastal ocean processes off Kalpakkam region. It provided information about the effect of seasonal circulation features on hot plume dispersion at the discharge location, thermal plume characteristics and influence of thermal plume re-circulation during pre- and post-monsoon seasons at the intake locations of MAPS and PFBR (two nuclear reactors operating at the Indira Gandhi Center for Atomic Research) in the region.

The dispersion of thermal water plume depends on atmospheric forcing parameters and coastal processes, which are complicated because of their non-linear interaction. The seasonal circulation features and movement of thermal plume dispersion with the seasonal wind and heat fluxes were also studied. To accomplish this, the Particle Trajectory Tracking Model (PTTM) was integrated with the hydrodynamic dispersion model in order to track the movement of nuclear effluent for a region within a few kilometers from the coast.

The development of flux coupling algorithm has been initiated to study the role of atmosphere and ocean forcing parameters on the near-shore environmental conditions. Kettle [8] has combined the General Ocean Turbulence Model and the Hadley Centre Ocean Carbon Cycle model to explore the dependencies of air-sea carbon fluxes on physical and marine biological variability. In the present study, the coupling algorithm acts as an interface between two independent state-of-art models i.e. atmosphere and ocean. It is well recognized that a modified flux coupling algorithm would be able to take care of the physical exchange processes across the atmospheric and oceanic surfaces [9]. Accordingly, in the present work a Flux Coupling Tool-Kit (FCTK) is developed that couples two state-of-art models, one for the atmospheric component (WRF model) and the other for the oceanic component (POM model). The development of FCTK is aimed to study these two models and integrate them to operate in routine weather forecasting. The developed FCTK improves the bonding between the two models by virtue of flux exchange at the interface. Several numerical experiments related to the study of the thermal plume dispersion from the outfall regions of two power plants at Kalpakkam have been conducted to assess the performance of RCAOM (Regional Coupled Atmosphere Ocean Model) by using the FCTK algorithm.

Utilizing the developed model codes, interface between the models, coupling and integration of models, the Decision Supporting System (DSS) has been developed over the years to characterize the interactive software for assisting the data, information and awareness for decision makers on complex issues. The DSS is a method where all relevant models are integrated to obtain realistic estimate of physical variables for a particular region. It involves integration of various state-of-art models for atmospheric forecast, shallow water, coastal and near-shore circulation prediction models all operated at one place.

The DSS is an interactive, computer-based system. It supports the users and an organization in decision making activities of a particular situation in advance. It provides data storage and retrieval and also enhances the traditional information access and retrieval functions with support for model building and model-based reasoning. It supports framing, modeling, and problem solving. A well designed DSS is an interactive software based system intended to help decision makers to compile useful information from the observed data and computer simulations to identify and make appropriate decisions.

Thus we have seen that the response and interaction among various components in a weather system is such a complex dynamical system that they cannot be achieved through a single-model simulation [10]. The fact that it is difficult for a single-model to fully model a three-dimensional coastal process is seen by the fact that most organizations go to multi-model coupled interacting models. Hence, the development of coupled models is very crucial to study and understand the general circulations of atmosphere and ocean. Coupled models are known to improve hindcast/forecast skills having wide practical implications [11]. One such application could be the tracking the effluent path trajectory in aquatic and marine environment. Some of the more complicated phenomena viz; thermal water transfer, currents, thermohaline meridional overturning circulation, ventilation, vertical mixing, land and sea breeze effects can also be properly quantified using these coupled models. Further, real-time operation of coupled models has proved its importance in prediction of economic fishing zones, finding optimum navigation routes and also in predicting effluent discharges in marine environment.

In the Indian scenario, the present users of operational oceanography products are mostly Government agencies and other research centers. There are two main operational centres in India, they are INCOIS and IMD. INCOIS provides the operational forecast of the oceanographic parameters like Sea Surface Temperature, ocean currents, wave parameters, potential fishing zones etc. This centre gives valuable oceanic forecast during the extreme weather conditions like cyclones and tsunamis. The other is India Meteorological Department (IMD), which gives the information and warnings regarding the weather events. It is mandated to take meteorological observations providing current and forecast meteorological information for optimum operation of weather/sensitive activities.

In this paper, we demonstrate how a real-time web-based decision support system based on a coupled atmospheric-ocean model help in attending to disaster management of industrial power plants in inland and coastal areas. Focus is also placed on developing a strategic plan for disaster prediction and management as an aid to scientific advisories.

Location of Present Study

As of 2015, India had a total of 21 nuclear reactors under various stages of operation situated across 7 nuclear power plants producing a total of 30,292.91 GWh of electricity. In addition to this, it is expected to have 6 more reactors producing 4300 MW within the next five years. Of these, one of the most important power plants is Indira Gandhi Center for Atomic Research, IGCAR located at Kalpakkam, Tamilnadu (Figure 1).

Kalpakkam is a city in South India with two vital nuclear power plant installations: Madras Atomic Power Station, having two reactors of 220 MW each, and Prototype Fast Breeder Reactor being constructed to accommodate 500 MW electricity, centered at the Indira Gandhi Centre for Atomic Research (IGCAR) under the Department of Atomic Energy, Government of India. Located south of Chennai and further towards the coast, the MAPS reactor takes coolant water from the intake location and expels the waste/thermal water through an outfall, both the intake and outfall being 1 km apart. The near-shore currents follow the monsoonal reversal of winds, with the current being towards the north from Feb-Sept and southwards the rest of the year.

Radiological Safety Division at IGCAR which monitors the atmospheric weather forecasts, the spread of nuclear pollutants and other safety measures, has a web based Decision Support System (DSS) in place for atmospheric weather forecast in case of radiological emergencies. There was no DSS in place to predict the sea conditions. Keeping this in consideration, there was a need to develop a DSS for ocean component at IGCAR, Kalpakkam and the author's research team has been doing it. In this short paper, we write about power plants' preparations to disasters whether natural or man-made. We also discuss on some strategies that need to be implemented that will go a long way in reducing the impact of such disasters. The policies have been framed on the basis of some new schemes implemented by the incumbent government in India - digital India and National Knowledge Network scheme (NKN). Also a relatively novel technique of drawing up a vulnerability index (or threat-level) based on particle trajectory tracking model (PTTM) is suggested.

In the past, the nuclear plants in Kalpakkam were forced to shut down couple of times due to extreme water elevations. Also the 2004-December Indian Ocean tsunami resulted in severe loss and damage to

coastal infrastructure. In context to safety measures, if there existed a forecasting system that could evaluate and quantify the various risks from cyclones, extreme sea level rise and rough weather conditions, it would provide immense support to decision making, and aid in mitigation activities.

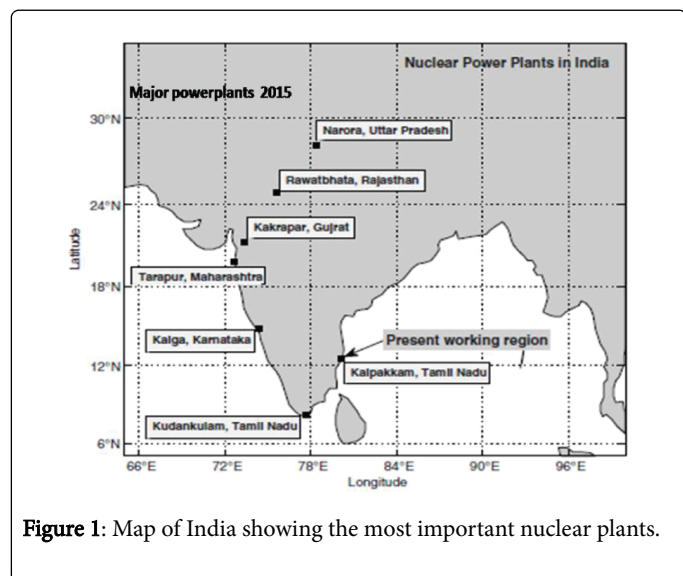


Figure 1: Map of India showing the most important nuclear plants.

Nuclear Disaster Management

We can categorize the nuclear reactor disasters into two categories. In the first category are the natural disasters that cause damage to nuclear reactors and hence cause leakage. Most of the nuclear reactors being located near the coasts, there is an increased chance of being exposed to cyclones [12], tsunamis and storm surges. The second category of disasters occurs due to human actions. It could be an accidental leak due to some fault in the reactor equipment or buildings, or due to some malicious activities.

We believe the approach to these two types of disasters should be different. A natural disaster like a cyclone can be predicted at-least a day early (maybe even a week). This is sufficient time for a power plant to issue warnings to the public if a fool-proof system of forecasting weather and geophysical events are in place along with a robust network of communication channels that will take the information about the oncoming disaster to the entire public in a fast and efficient manner. On the other hand, man-made disasters like an accidental leak of nuclear effluents, or a lapse in the treatment of nuclear waste are totally unpredictable events. So, all we can do about preparing for one such event is to draw up a vulnerability map showing the various nearby areas with their respective threat levels. We claim that running particle trajectory models in numerical ocean models for various seasons and taking an average over the year will give us a very good estimate of the threats to various locations. Once these areas are identified, high precaution in these regions would go a long way towards reducing the damages to both life and property there.

Natural Disasters

Natural disasters that can affect the power plant in Kalpakkam are mainly cyclones that mainly occur during April – September, storm surges associated with cyclones [13], and a possible tsunami. As we mentioned before, the approach to such natural disasters lies in

‘knowledge forecast and dissemination’. Proper knowledge of the disaster beforehand and well-preparedness when translated into immediate actions, would help mitigate the loss to the people.

So as part of this ‘knowledge forecast and dissemination’, we have developed a real-time ocean forecast system which predicts the ocean state for a future 2 days and also displays it on the local intranet of the IGCAR. We propose that this forecast should be broadcast on the NKN network to a few institutions (details given later in the paper).

Forecast: We first report the development of a coupled model for application to IGCAR coastal waters (called IITCAOM) providing output to a web-based operational forecasting system. For its ocean model component, we have used the Princeton Ocean Model (POM). POM is an ocean model that runs in either the 2 dimensional or 3-dimensional mode, and solves a primitive equation model with sigma vertical co-ordinates. First version of POM was developed in the late 1970’s by Blumberg and Mellor for modeling of hydrodynamic flow properties in open oceans and coastal regions. It has different versions like non- Boussinesq version of POM, two-dimensional version of POM, MPI and HPC parallel versions of POM contributed by professionals. Based on this ocean model and an atmospheric model already in place, we can design a coupled atmosphere-ocean model decision support system.

Decision Support System [6] is a computer based information system that supports decision making process achieved by exchanging the information using models or analytic techniques with traditional data access well in advance of the event. The DSS designed at RSD IGCAR, Kalpakkam integrates the information from meteorological and ocean models for final dissemination of thermal water movement and effluent trajectories that can be hazardous to the local community around nuclear plants during accidental situations. Quality checks are performed at each step of workflow within the frame work of modeling system that comprises suite of state-of-art models such as WRF (Weather Research and Forecasting Model), POM (near-shore water model), Flux coupler (Interface between two state-of-art models) and PTT (Particle Trajectory Tracking Model). The DSS is a dedicated system that works 24×7 providing vital information to RSD at IGCAR, Kalpakkam whether during normal times or during emergency.

The developed ocean part of the realtime model could be used to calculate ocean currents, thermal water dispersion etc along the Kalpakkam coast to be web-published for the decision support system (DSS) which has been prepared using the HTML Script. The website provides information on thermal water movement and variation of SST along the Kalpakkam region. This model output is maintained in web based operational forecasting system for ocean currents, thermal water dispersion along the Kalpakkam coast for the decision support system (DSS). The website (Figure 2) provides information about thermal water movement and variation of SST along the Kalpakkam region. The sample forecast of thermal plume and circulation features and variation of salinity is shown in Figure 3. The goal is to provide a 2 days forecast of ocean currents, thermal water dispersion and effluent trajectories in the existing DSS at IGCAR, Kalpakkam, which works on a 24×7 mode that comprises of necessary computational, communication and technical support infrastructure facilitating data reception, display, analysis and modeling for generation of advisories following standard operating procedures.



Figure 2: Designed website for the operational ocean currents and thermal water dispersion forecasting system for the Kalpakkam coast.

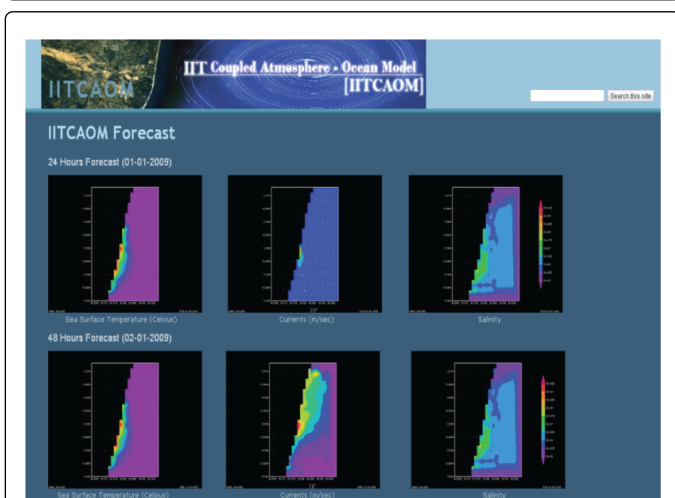


Figure 3: Illustrated forecast of the thermal water dispersion and circulation features along the Kalpakkam coast as shown on web page.

The current patterns were studied for four months of the year 2009 (April, July, September, and November) and are shown in Figure 4. All the years are similar to these plots which are produced in real-time now. The simulation shows northeastward currents following the southwest winds during April, July, and September with maximum currents of 0.2 ms^{-1} during July. There is a reversal in direction because of wind changes, and from September to February they flow southwest. The current magnitude during this period reaches up to

0.18 ms^{-1} . The temporal and spatial spread of the thermal plume has also been studied in detail (but not shown).

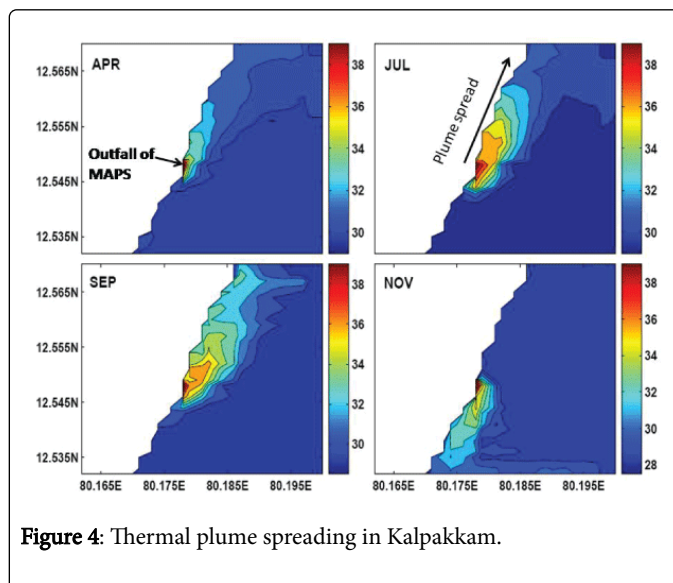


Figure 4: Thermal plume spreading in Kalpakkam.

Dissemination of the information: A new direction of implementation is suggested here for the future for maximal utilization of the country's resources and for disaster management in the light of the new policies incorporated by the Central Government – the Digital India and National Knowledge Network (NKN) scheme.

This network (NKN: <http://nkn.in/home>) project has been devised by the Indian government to provide a digital infrastructure and network across the whole of the Indian subcontinent using high bandwidth/low latency connections. A large number of (more than 1500+) of institutions have been connected through this project to form a unified high performance computer network across various states. The network is secure and can transfer large quantities of data real-time. Due to its high potential, we feel it can be used in our policy framework (Table 1).

The DSS set up as real-time in IGCAR should be used to send data to NKN institutions in the neighborhood especially the educational/university institutions. Model is run in the DSS and spreading of the plume is reported as FORECAST for 2 days. This forecast is to be then relayed to the institutions mentioned in Table 1. We have identified the following (in Table 1) as the institutions in the nearby areas that can serve as secondary nodes for these forecast relay. These universities should have ways of disseminating the output of DSS to the common man. They can advertise in local newspapers, radio, TV and web-site and by training their own personnel or students. All natural disasters influencing the IGCAR nuclear power plant will then be predicted by the real time simulations and preparations can be done accordingly (Figure 5).

No	Name of institute	Type
Node	Indira Gandhi Centre for Atomic Research, Kalpakkam	Atomic Energy
1	National Centre for Sustainable Coastal Management, Chennai	Research/Teaching

2	National Institute of Ocean Technology, Chennai	Research	
3	Indian Institute of Technology (IIT), Chennai	Engineering	
4	Madras Institute of Technology, Chennai	Engineering	
5	CDAC Chennai	Computing	

Table 1: List of NKN institutions in the vicinity of Kalpakkam.

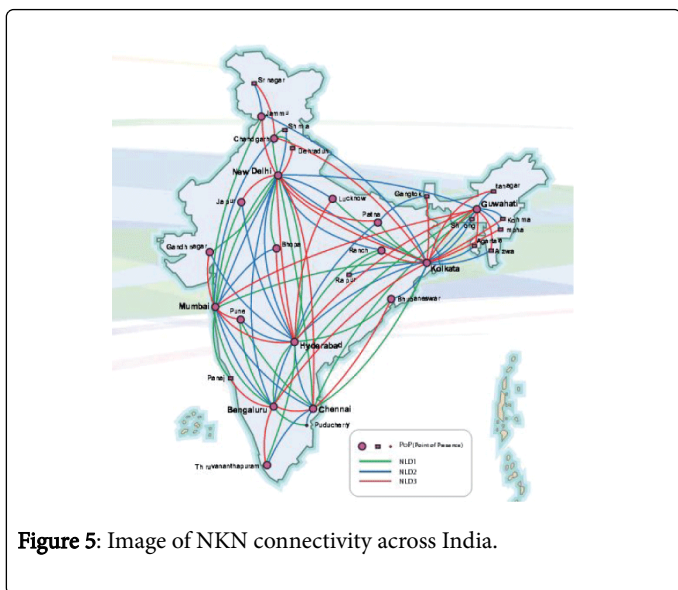


Figure 5: Image of NKN connectivity across India.

Man-Made Accidents

One of the main focuses of our paper here is in safeguarding the public interests if a man-made nuclear power plant calamity occurs. Usually there is no preparing time for such events– nuclear leakage is likely to happen fast – and thus the government and people do not have any response time. The unpredictability of this event makes it more dangerous than natural disasters though its occurrence might be rare. Therefore we need to assess the vulnerability of the environment to such threats.

Vulnerability as defined in the context of disaster management implies assessing the potential threats to the public due to the operation of the particular industry, and an assessment of the dangers due to the waste itself or any leakage of the waste. Vulnerability analysis is a study of the risks to the nuclear reactor itself and further implications to the immediate surrounding environment. From the analysis we can make better policies to prevent any such activities in the future and also avoid such incidents of leakage in the future [13].

PTTM: The PTTM [14] is incorporated on to the original Princeton Ocean Model. For the current simulations, PTTM thus incorporated into POM is used for trajectory tracking done in each subsequent time step. Special flags have been put to check if the particle has entered land. The particle moves along the grids of the model which are kept constant but curvilinear. A trajectory simulation result for the year 2009 is shown in Figure 6 for a small time period. The particle moves further and is tracked for a month. The integrated model takes into account the average current speed from the dispersion model and provides it to the PTTM. This in turn considers the initial position of

the particle at the point of the outfall. The model is run for all months separately (for the year 2009) to obtain their individual particle trajectories. These are plotted with the bathymetry data, which include the coastline to show the position of the particle against depth variation. The positions of the particles primarily depend on time, depth, and current speed, though there are some second order factors as well. During April and July, the trajectories follow the current patterns, and the overall movement is in the northeast direction. The particle track for the month of September is not exactly toward the north or northeast like the current direction, but has a tendency to move toward the north before finally heading toward the east. Tracking the particles for the month of November shows a southward trend aligned with the existing current pattern. The particle trajectory during the month of July also represents the northeastward movement of that month.

In this paper, we propose that the vulnerability maps should be based on this particle trajectory tracking model [15]. In the PTTM subroutines incorporated into the Princeton Ocean Model, we use the outfall location as the starting point and incorporate the actual meteorological forcing to follow the trajectory of particles. Then, the time average of the deposit locations of the effluents or the points where the effluent finally end up are considered as vulnerable points in the Chennai map. Since during most seasons of the year the flow in this vicinity is towards north and north east, this direction of IGCAR can be considered to be more vulnerable to man-made disaster-impact. So, the vulnerability map (Figure 7) shows that the area to the north of the effluent discharge location has the maximum vulnerability to accidents. This is the sector where maximum preparedness is required.

Conclusions

In this paper, we have tried to illustrate some options for dealing with natural disasters in the wake of new plans implemented by the Govt. of India – digital network and digital infrastructure. We believe this network can be used to spread the awareness and strategic knowledge of how to deal with natural disasters like cyclones and tsunamis especially in the vicinity of nuclear plants. The sharing of information between the IGCAR (department of atomic energy) and the local institutions connected to NKN can implement the safety measures and precautions of the general public against calamities simply by knowing how to handle the problem. We have also shown how the numerical ocean/atmospheric trajectory tracking models can be used in preparing a vulnerability map for the surrounding environment. Preparing this map will help us localize our problem area and more focus can be put in that region to reduce human suffering.

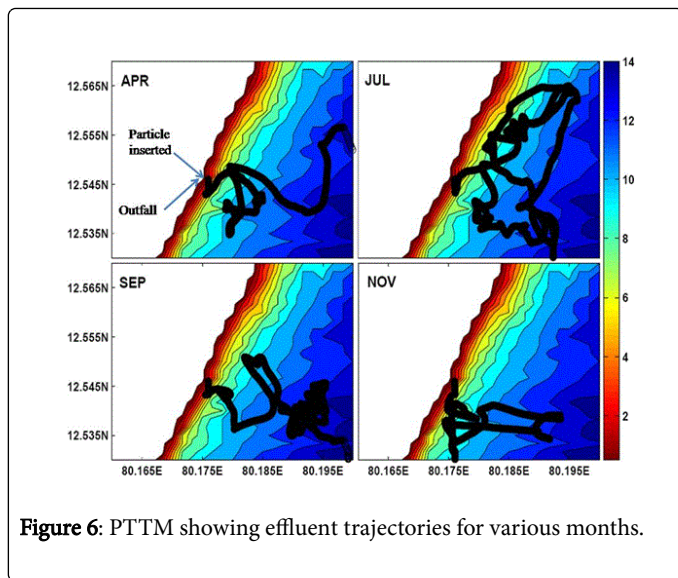


Figure 6: PTM showing effluent trajectories for various months.

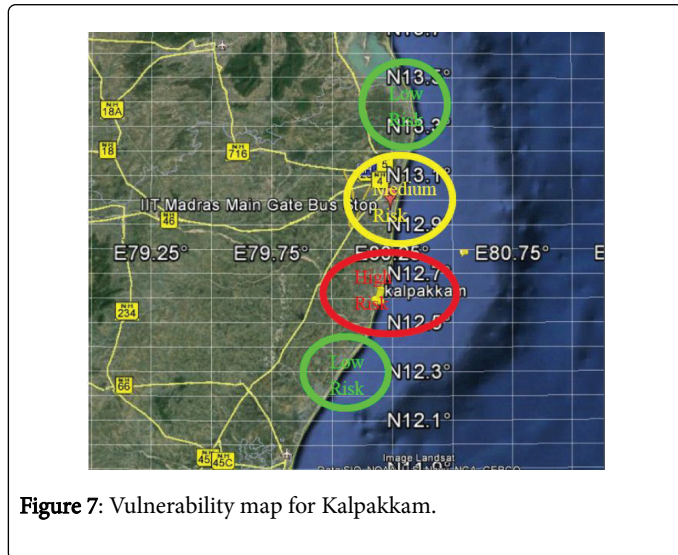


Figure 7: Vulnerability map for Kalpakkam.

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