Application of geospatial technology in assessing impact of coastal flooding due to 2004 tsunami - A case study covering a part of Tamilnadu coast, India

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Abstract: The GIS technology enables in integration of various aspects of flood and provides valuable tools to assess the extent of flooding. This paper proposes to utilize the full potential of both RS and GIS techniques in deriving a geospatial model for delineating the susceptible inundation areas for Kalpakkam plant site. A high resolution Digital Elevation Model (DEM) was generated using LIDAR data delineated inundation patterns employing integrated techniques in GIS environment. The geospatial model results have been validated with actual 2004 tsunami event and also compared with outputs from shallow water model Anuga. The results obtained from geospatial model were in good agreement with actual tsunami inundation patterns. It has been observed from the study that the maximum variation of inundation distance was within 50m for 82% of observed locations at every 500m interval. On the other hand, the comparison of geospatial model results with Anuga model results showed only 32% of observed locations within the distance of 50m. The spatial overlap for model predicted results with respect to actual tsunami inundation data was ranging between 76.6% and 93.7% for the six villages in the study area. The present study also discusses the novel approach adopted using vector-based contiguity analysis.

Keywords: SDSS; GIS; geospatial model; flood inundation; contiguity analysis

1. Introduction

Flood hazard is one of the serious concerns worldwide, particularly in the coastal areas where the potential risk of flooding increases due to sea level rise caused by tsunami/cyclone etc. To understand the complex reality of flood hazards, it is essential to devise a Spatial Decision Support System (SDSS) which can assess a specific site during likely flood hazards. It can also help to reduce decision-making time (Malczewski, 1997) during real flood situations.

Remotely sensed satellite data with high spatial resolution provides information on the extent and spatial distribution of inundation areas. The Geographical Information Systems (GIS) based decision support can play a vital role in monitoring, controlling and assessing natural hazards (Zhang et al., 2002) to facilitate solution of complex environmental problems, especially for flood hazards. The GIS in recent years has provided a spatial reasoning system which is having the ability to analyze, validate, maintain knowledge bases etc. (Holt and Benwell, 1999), thus helping to generate geospatial models. GIS is an efficient decision support tool. It helps in synthesis of data and to map the relationships between hazard phenomena and vulnerability (El-Ray, 1997; Zerger, 2002). The necessity for providing geospatial model thus became very essential for environmental problems like flood inundation.

In a national round robin numerical exercise pertaining to Sumatra 2004 tsunami, it was observed that the numerical model results are predicted reasonably well in run-up estimation by the participants. However the extent of inundation was over predicted (Sasidhar et al., 2009). In the present study, an attempt is made to develop a geospatial model for Kalpakkam plant site as a part of site-specific SDSS for flood hazard and analyze the potential of the model in real flood scenarios, using remotely sensed earth observation data and GIS tools. A novel approach using vector-based GIS method was attempted to delineate the inundated zones ensuring the contiguity with shoreline.

2. Study area and tsunami 2004

The study area is Kalpakkam nuclear power plant site, which is situated about 70km south of Chennai, India (Figure 1). The study area lies between 80^0 09' to 80^0 13' E longitude and 12^0 42' to 12^0 29' N latitude. The study area is bounded by Bay of Bengal in the east and also includes the nearby villages viz., Kokilamedu, Edaiyur, Kalpakkam, Meiyur, Sadurangapattinam and Pudupattinam on the coast.

The study area is situated on the Tamilnadu coast which was affected due to tsunami 2004. Ilangovan et al. (2005) and Subramanian (2006) have independently reported the run-up in the range of 1 - 6m during tsunami 2004 along Tamilnadu coast. The Kalpakkam plant site was largely unaffected due to tsunami 2004. However the Kalpakkam Township experienced a major impact. Several remedial measures were undertaken at Kalpakkam Township and the normal life was restored on various fronts in less than 6 months time (Baldev Raj et al., 2006).

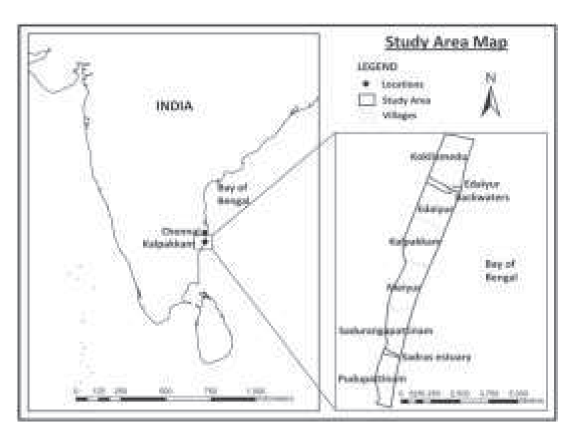

Figure 1: Study area

3. Geospatial modelling

The development of geospatial model broadly involves two phases namely, the design phase and the implementation phase (Figure 2). The design phase involves five components (Abdul-Rahman and Pilouk, 2008) viz., object type, relationship, attributes, convention and operation. The relationships between object types are interpreted in the conceptual design phase to convert the perception of reality into modeling scheme. The attributes of objects and their relationship are employed in the logical design phase to implement the geospatial model. The conventions comprise a set of integrity and consistency rules that must operate in every design phase. The data are accessed, processed and stored in geospatial model to implement the operations.

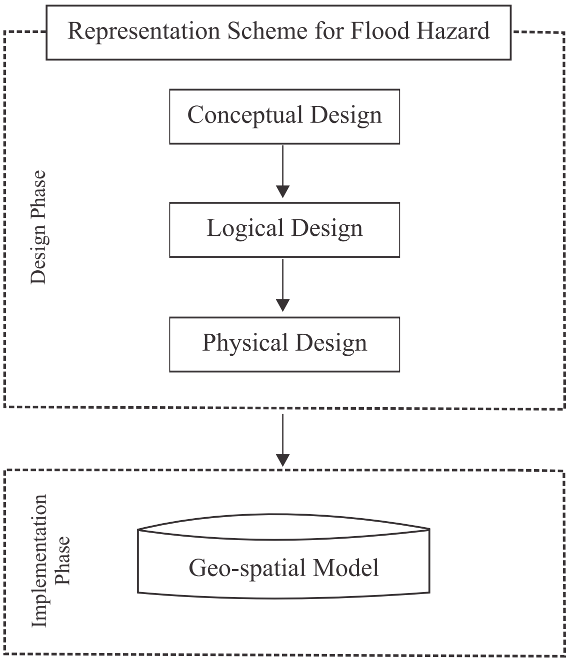

Figure 2: Design and implementation phases of geospatial model for flood hazard assessment

4. Design phase

In the present study an attempt has been made to implement a geospatial model for flood inundation at Kalpakkam plant site, using remote sensing and GIS technology based on the flood scenarios envisaged.

4.1 Conceptual design

A conceptual coastal flood event was envisaged to analyze the influence of land topography in coastal flood inundation. A typical coastal flood hazard scenario is shown in Figure 3.

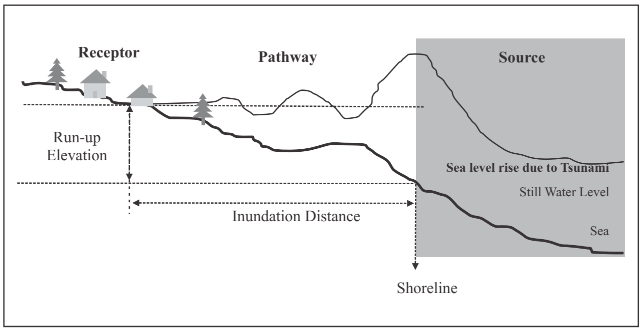

Figure 3: Cross-sectional view of typical coastal flood hazard

Based on the above scenario, the following conventions are made to ensure the design requirements with respect to conceptual design aspects.

- The areas with elevation higher than flood run-up will not be inundated and the areas with elevation lower than or equal to the flood run-up will be inundated.
- The inundated areas necessarily have to be connected or contiguous to the shore hydrologically.

4.2 Logical design

Run-up is the essential component to implement the site-specific flood model using topographic data. The average run-up for the tsunami 2004 event was reported as 4m based on the surveyed locations (Ilangovan et al., 2005). The average tsunami run-up for Kalpakkam plant site was arrived at 3.97m based on the results of round robin exercise (Sasidhar et al., 2009). The wave hind casting studies also have predicted a wave height of 4.3m for a 50 year return period for the coast at Kalpakkam (IGCAR, 2006). During the field survey after tsunami 2004, the run-up values recorded at specific locations in plant site were between 3.3m and 4.5m. Based on the field data and the literature inputs, a 4m run-up has been chosen for the present study.

Figure 4 presents the flow diagram of geospatial processes in flood model. Based on the input run-up value, the model delineates susceptible low elevation areas. The connectivity of these delineated areas with shoreline is verified to ensure the hydrological relationship. Finally the model output offers susceptible flood inundation area for any given run-up.

4.3 Physical design

Once the conceptual design aspects and logical design requirements were prepared, the next step is choosing the right method to implement the model. Based on the GIS aspects, there are two models are available viz., raster and vector.

A raster based approach to map the extent of inundation was attempted earlier by Pathan et al. (2005) using geospatial techniques. In the present study, a novel approach using vector-based GIS method was attempted to delineate the inundated zones ensuring the contiguity with shoreline.

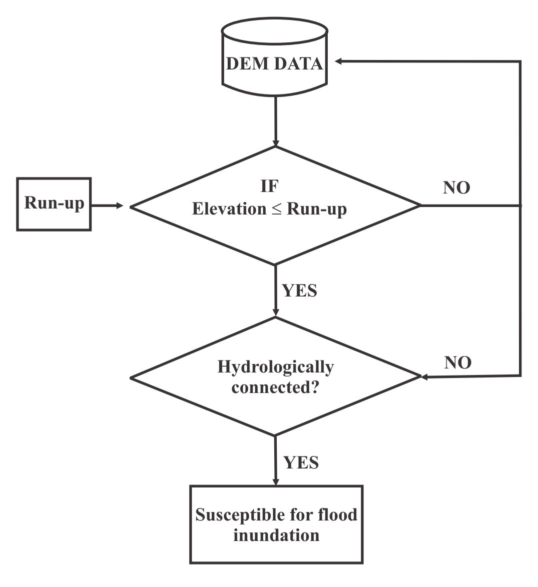

Figure 4: Flow diagram of geospatial processes

5. Implementation methods

The software packages, ESRI ArcGIS 9.3 and ERDAS 9.1 were utilized in the study for geospatial analysis and evaluation of impact. The GIS based methods and techniques employed in the implementation are described below.

5.1 Development of digital elevation model

The terrain data with high resolution and accuracy are essential elements in assessing the pathway and inundation of flood hazard. Digital Elevation Model (DEM) data has the topographical values of the coastal land. A high resolution DEM was derived from LIDAR data (Sasidhar et al., 2009). A natural neighbour interpolation algorithm (Bater and Coops, 2009) was used for the generation of site specific DEM in GIS environment. This has about 600 thousands point data with 1m x 1m spatial resolution and 0.1m of vertical accuracy. This site-specific DEM is shown in the Figure 5.

The DEM data generated in GIS environment possess the elevation and spatial information in raster format for each pixel. These pixel values of DEM data were categorized based on elevation using GIS based reclassification techniques into required intervals (≤ 4m and > 4m). The reclassified DEM data were vectorized for the purpose of contiguity analysis using GIS based raster to vector conversion technique (Congalton, 1997). After removing the slivers, the adjoining polygonic regions with same elevation values have been merged using dissolve techniques in GIS (Martinez-Llario, 2009).

Using so derived polygons and shoreline map, a spatial contiguity analysis was attempted. Based on this analysis, the polygons meeting the run-up stipulation are considered, provided the polygons intersect or share a boundary with the shoreline. The two estuary channels viz., Sadras estuary and Edaiyur backwaters were excluded in the zone of simulation to minimize over estimation of flood impact.

Figure 5: Site-specific DEM

5.2 Prediction of impacts

Decision-making at district/state level authorities, environmental regulators, emergency managers etc., require scientific computational results and quantified information about the consequences of flood hazard to initiate pre-hazard assessment or post-hazard mitigation actions. The geospatial model devised for 4m run-up was employed for every 1m interval. The flood zones delineated are utilized effectively to assess the impact on environmental features using geo-computation techniques. Accordingly, the flood zones were integrated over land use/land cover thematic map using GIS overlay techniques and the flood impact on land use/land cover categories was extracted. The above technique was also employed to assess the extent of area affected in each village by overlaying flood zones over village boundary map. The area of impact identifies the severity of flood hazard whereas percent of impact determines the significance of hazard over particular village or land use category. The results obtained for area of inundation and land use impact are discussed below.

5.2.1 Village level prediction of impacts

The inundation impact predicted on coastal villages is presented in Table 1. The area of inundation within a village obtained from the spatial model falls between 14% and 25% for the villages Edaiyur, Kalpakkam, Kokilamedu and Meiyur. It could be seen from the Table-1 that the area of inundation for two typical villages viz., Pudupattinam and Sadurangapattinam are 1.05 km^2 and 0.86 km^2 respectively. Whereas the % of inundation area with respect to total area of these villages were 64% and 53% respectively. This is attributed to low-lying areas adjoining the Sadras estuary. However during rehabilitation stage, the data on area of inundation as well as % area of village affected will be of immense use to village authorities to allocate rehabilitation funds rationally.

Table 1: Village-wise prediction of impact of flood inundation in the study area

Name of the Village	Coast area Studied (m^2)	Inundation area (m^2)	% of inundation
Edaiyur	2454713	514966	21
Kalpakkam	2617856	359661	14
Kokilamedu	2764529	612852	22
Meiyur	2204765	546438	25
Pudupattinam	1657456	1054968	64
Sadurangapattinam	1626910	861754	53

5.2.2 Land use categories wise prediction of impacts

The predicted impacts due to the flood inundation on the categories viz., Barren Rocky/Stony waste, Built Up (Urban), Built Up (Rural), Coastal Natural, Crop Land, Fallow, Forest Plantation, Habitation with plantation, Lakes/Ponds, Marshy/Swampy, Plantation, Sandy area and Tanks (Pathan et al., 2005) are provided in Table 2. The major land use category, the sandy area was inundated to the extent of about 45%. Marshy/Swampy, Tanks and coastal natural were badly affected land use categories with impact of 83%, 76% and 63% respectively. It could be seen that the land use categories viz., Barren Rocky/Stony waste, crop land, lakes/ponds and plantation area were not impacted as these land farms are situated away from the coast and also at higher elevation. The analysis of impact zones will be helpful in utility planning for locating a place which is having specific land use, safe level of flood susceptibility, desired distance from unsafe flood zones etc.

5.3 Interfacing the geospatial model with SDSS

The purpose of incorporating this model into SDSS (Sankar Ram et al., 2008) is to provide an interface that allows visualization and overlay analysis of spatial data and to consolidate all the information necessary for assessing and analyzing the flood scenarios spatially (Sasidhar and Sankar Ram, 2010). The GIS functions and programming techniques are encapsulated into this interactive system to enhance decision-making. The impact due to various scenarios using a query shell associated with the given database are generated and compiled for quick retrieval and application by decision-makers. The GUI developed guides the client through the application with a user friendly approach. The system has been designed so that no prior GIS knowledge is required to utilize the system.

Table 2: Prediction of impact of flood inundation on the Landuse categories in the study area

Land use Categories	Total area (m^2)	Inundation area (m^2)	% of inundation
Barren Rock/ Stony waste	103610	-	-
Built Up (Urban)	1605954	408356	25
Built Up (Rural)	96402	18982	20
Coastal Natural	471009	296916	63
Crop Land	127815	-	-
Fallow	352396	96768	28
Forest Plantation	3089625	394869	13
Habitation with plantation	3369693	841621	25
Lakes/ Ponds	42530	-	-
Marshy/ Swampy	34714	28876	83
Plantation	16776	-	-
Sandy area	3822671	1700371	45
Tanks	105761	80281	76

The geospatial model devised for 4m run-up was employed for every 1m interval to provide an effective environmental decision support. The well-organized GUI provides an option to select run-up from 1m to 5m. For example, if a user wishes to ascertain the impact due to a 3m sea level rise, the user can select the "Water Level - 3m" option to visualize the flooded area. In addition, a user may visualize the impact for land use categories by appropriate queries. Also, the user can measure the maximum inundation at a particular location using a distance measurement tool. The system allows the user to get the tabular summary of the flood impact over the land use categories and socio-economic data of the affected villages of interest by interactive mouse operations. The system also has rudimentary map navigation functions such as zooming-in, zooming-out, panning etc., to explore the map window.

6. Comparison of geospatial model results with tsunami 2004 data and Anuga outputs

The results obtained by geospatial model were compared with outputs from shallow water model Anuga and also with actual tsunami 2004 inundation patterns. Anuga model is a shallow water wave equation based hydrodynamic model which predicts the inundation for tsunami. Figure 6 shows the spatial distribution of model results, tsunami 2004 flood impact (Pathan et al., 2005; Sasidhar and Sankar Ram, 2010) and Anuga model outputs (Rajaraman and Winston, 2009).

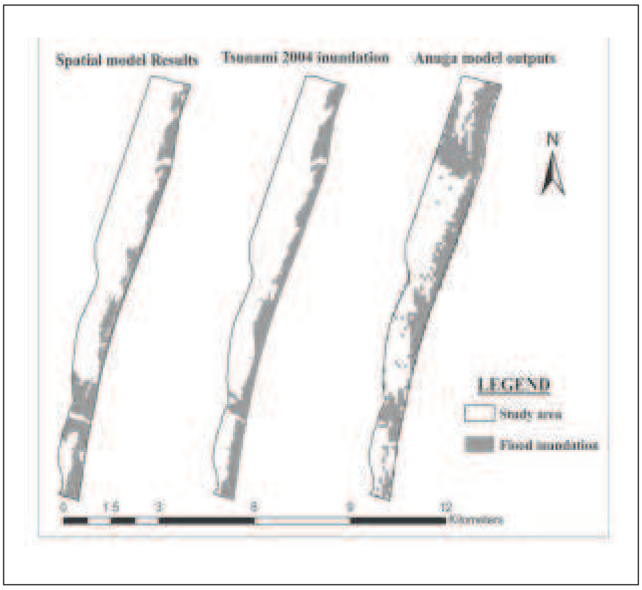

Figure 6: Spatial distribution of model results, tsunami 2004 flood impact and Anuga model outputs

6.1 Comparison based on inundation distance

For better appreciation of model results the maximum inundation at every 500m interval for the above three cases are tabulated in Table 3. It could be seen from the Table 3 that the geospatial model results were in very good agreement with actual tsunami 2004 inundation. For 82% of observed locations, the variation was within 50m. However a disagreement was observed between geospatial model and actual tsunami inundation near Sadras estuary. Another interesting feature being that the majority of geospatial model outputs were underpredicted compared to actual tsunami 2004. This is on expected lines as the geospatial model is conceptualized considering only two criteria viz., topography and upstream flooding and did not include contribution from wave velocity. Also the comparison between results of geospatial model and shallow water wave equation based hydrodynamic model Anuga outputs was not very satisfactory as only 32% of observed locations were within the distance of 50m.

Table 3: Comparison of predicted inundation at every 500m intervals on the coast with Tsunami 2004 data and Anuga Model outputs

Locations	Inundation from Tsunami 2004 (m)	Inundation from geospatial model (m)	Inundation from Anuga Model Outputs (m)
1	417	403	695
2	182	164	506
3	418	351	505
4	526	493	1394
5	238	207	248
6	231	244	248
7	305	266	356
8	131	121	359
9	236	231	578
10	251	256	457
11	267	269	227
12	317	332	652
13	426	414	651
14	387	368	363
15	175	252	292
16	190	81	No data
17	292	284	318
18	692	662	615
19	294	762	702
20	342	392	54
21	361	365	65
22	446	454	297

6.2 Comparison based on inundation area

The comparison of inundation area obtained from geospatial model for 4m run-up with tsunami 2004 inundation is shown in Table 4. It could be seen from Table 4 that the geospatial model outputs are in good agreement for four villages viz., Edaiyur, Kalpakkam, Kokilamedu and Meiyur. The agreement between the predicted results (P) and the actual area of inundation (A) due to tsunami 2004 were within 2 - 5%. However, the model results (P) appeared under predicted. In the case of remaining two villages viz., Sadurangapattinam and Pudupattinam the model results were over predicted. As indicated earlier, this higher inundation is attributed to low-lying areas adjoining the Sadras estuary.

The spatial intersection between the predicted results (P) and the actual area of inundation (A) was computed using GIS tools. The spatial intersection ($P \cap A$) between the predicted

Table 4: Comparison of village-wise predicted area of inundation with Tsunami 2004 data

Village Names	Total area in m^2 (T)	Predicted area of inundation in m^2 (P)	% of (P) w.r.t. (T)	Actual area of inundation Tsunami '04 in m^2 (A)	% of (A) w.r.t. (T)	Spatial intersection or overlap area in m^2 (P ∩ A)	% Spatial intersection (P ∩ A) w.r.t. (A)	% Spatial intersection (P ∩ A) w.r.t. (P)
1	2	3	4	5	6	7	8	9
Edaiyur	2454713	514966	20.98	562031	22.90	486770	86.61	94.52
Kalpakkam	2617856	359661	13.74	427963	16.35	327730	76.58	91.12
Kokilamedu	2764529	612852	22.17	724299	26.20	591800	81.71	96.56
Meiyur	2204765	546438	24.78	665451	30.18	537000	80.70	98.27
Pudupattinam	1657456	1054968	63.65	750638	45.29	702935	93.65	66.63
Saduranga-pattinam	1626910	861754	52.97	668288	41.08	575626	86.13	66.80

results (P) and actual inundation data (A) are presented in Table 4. It could be seen from the Table 4 that the spatial intersection or overlap with respect to tsunami 2004 inundation data (Col. 8) was ranging between 76.58% and 93.65% for the six villages in the study area. This high degree of overlap of % spatial intersection suggests the applicability of geospatial model in real flood scenarios. Also it could be seen from the Table 4, the spatial intersection with respect to predicted results (Col. 9) was in the range of 66.63% to 98.27%. A large deviation observed in the case of Pudupattinam and Sadurangapattinam has already been discussed earlier, is attributed to low-lying areas adjoining the Sadras estuary. The outputs from the model have demonstrated the relevance of geospatial modeling approach in flood hazard assessment.

7. Salient conclusions

The geospatial model proposed in the study will help to improve the understanding of decision makers regarding flood inundation using geospatial analysis tools. The results obtained from this case study were in good agreement with tsunami 2004 inundation shows that the geospatial techniques have great potential in flood hazard management. It has also been observed from the study that the geospatial model results showed substantial improvement in prediction over numerical simulation model outputs.

Implementation of this geospatial model into SDSS operates most effectively through interventions in three aspects viz. i) help regulators identify the coastal locations that are suitable for green field sites in external flood hazard perspective, ii) identification of vulnerable areas where barriers have to be engineered for the existing coastal sites and iii) identification of safer locations for utilities like waste management facilities during infrastructure planning and development. The model can also be employed to generate a suite of likely impacts for different flood scenarios and maintain a periodical geo-database. In case of emergency, geo-database can be retrieved and utilized for handling the flood by the decision-makers.

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