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THE TSUNAMI ASSESSMENT MODELLING SYSTEM BY THE JOINT RESEARCH CENTRE

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ABSTRACT

The Tsunami Assessment Modeling System was developed by the European Commission, Joint Research Centre, in order to serve Tsunami early warning systems such as the Global Disaster Alerts and Coordination System (GDACS) in the evaluation of possible consequences by a Tsunami of seismic nature. The Tsunami Assessment Modeling System is currently operational and is calculating in real time all the events occurring in the world, calculating the expected Tsunami wave height and identifying the locations where the wave height should be too high. The first part of the paper describes the structure of the system, the underlying analytical models and the informatics arrangement; the second part shows the activation of the system and the results of the calculated analyses. The final part shows future development of this modeling tool.

1. INTRODUCTION

The Joint Research Centre of the European Commission is operating the Global Disasters Alerts and Coordination System (GDACS, http://www.gdacs.org) since 2003. This System, jointly developed by the European Commission and the United Nations, combines existing web-based disaster information management systems with the aim to alert the international community in case of major sudden-onset disasters and to facilitate the coordination of international response during the relief phase of the disaster. When new natural disasters events occur automatic analysis reports are created and sent to the users by mail, fax or sms.

As a consequence of the 26th December Tsunami JRC included Tsunami modeling in the GDACS system in order to improve and complete the automatic reporting system. At the beginning of 2005 a travel time wave propagation model was included (Annunziato 2005). This model calculates the wave arrival time independently on the initial tsunami wave height. In 2006 a new analytical tool has been developed in order to be able to provide also the height and identify the locations with higher risk of tsunami damage.

This report describes the JRC Tsunami Assessment Tool, which is a complex computer arrangement whose objective is to calculate the prediction of the tsunami behaviour when minimal parameters are known, that is the condition when an earthquake is firstly identified. Therefore knowing the position of the earthquake (lat/long) and the Magnitude of the event, the programme will calculate the fault characteristics, the Tsunami generation and displacement, the identification of the location on the coast, which will be mostly affected. As such, although it was developed for the GDACS system, it can serve any Early Warning System.

2. TSUNAMI GENERATION

When an earthquake is occurring and generates a Tsunami the following mechanisms occur:

- subsidence faults movements can result in rising part of the earth and lowering the opposite section (a seismic horizontal movement does not generally determines a Tsunami)
- the water above the fault rises of the same quantity (slip)
- a pulse wave is generated
- the wave travels even thousands of km in the ocean reducing its height due to energy distribution on a larger surface. Focusing mechanisms, due to reflections of the bathymetry or of the coasts may influence the wave height.
- an increase of the height (shoaling effect) and a reduction in width and speed occurs as the tsunami approaches the shore

A Tsunami modeling tool need to take into account the above mechanisms to proper describe the phenomenon. The wave behaviour prediction can be performed according to the following task list:

- evaluate the earth deformation caused by the earthquake and impose an initial water displacement as initial condition of the calculation

- calculate water wave propagation
- evaluate the run-up and estimate the impact to the coast

3. THE JRC TSUNAMI ASSESSMENT SYSTEM

The JRC Tsunami Assessment System integrates in a single programme several components that are needed in order to fully evaluate the Tsunami as a consequence of an earthquake event. When a new event is detected by the seismic networks the following parameters are known few minutes (15-30) after an event:

- Epicenter Latitude
- Epicenter Longitude
- Magnitude
- Earthquake Depth

The fault form and the fault movement are not known other than hours after the event due to the need to analyze seismic waves far from the epicenter. The JRC-SWAN programme estimates the fault length, height and direction (which will influence the initial water displacement), initializes the calculation space, performs the travel time propagation calculation, verify at each step if there are locations reached by the wave, update the visualization and animation files. The programme can run in manual interactive mode or in automatic mode.

3.1 Fault length

The analysis of past earthquakes indicates that it is possible to recognize a relation between the fault length and the magnitude of the earthquake, as shown in Figures 1 and 2 (Ambrasseys and Jackson 1998).

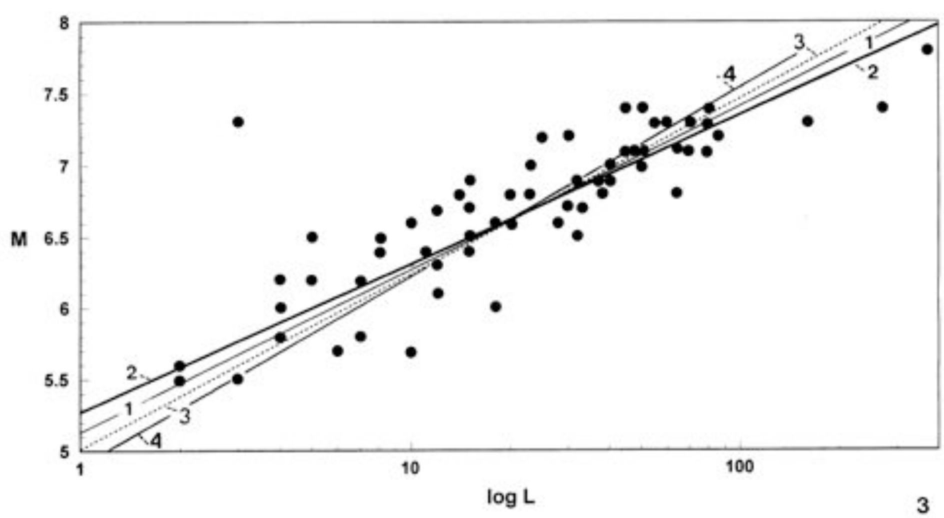


Fig. 1 – Ambrasseys et al: relation between fault length and magnitude

Several interpolation models exist for the evaluation of the fault length. Most of these models are of the following form:

Log (L) = A Mw + B

With L length in km, Mw is the earthquake magnitude and A and B two constants which determine the length of the fault. These constants are extremely sensitive because solving the above equation; the length has the expression on the right as an exponent of 10.

Taking, as an example (Ambrasseys and Jackson 1998) A=0.82 and B=-4.09, it is possible to see that

Mw=9.1, L=2355 km

Reducing the Magnitude to 8.5 the length becomes 758 km. In the following section we will adopt the formulation by Ward (2001), with A=0.5 and B=-1.8, which gives a value of 501 with a magnitude of 9. The two models become equal for a magnitude about 7. In the Sumatra case (9.1), the Length of the fault was about 1000 km, so the above equation can be a good starting point for the evaluation of the fault length, (Fig. 2).

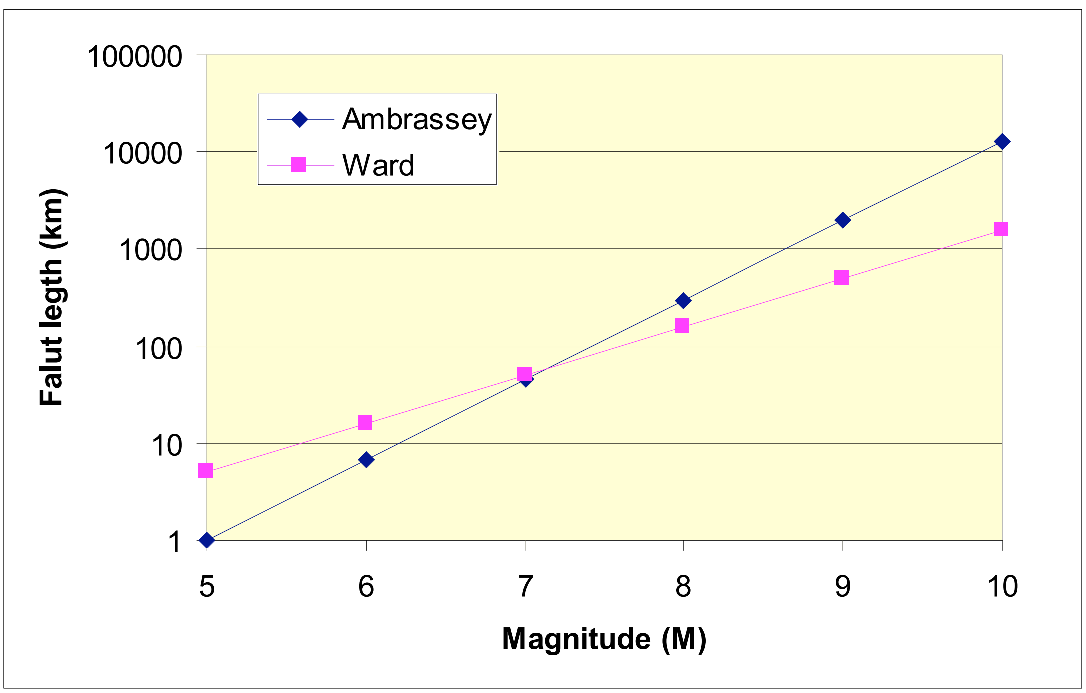


Fig. 2 - Relation between magnitude and fault length: comparison of two models

3.2 Water level increase at epicenter

As the earth is moving by L, determined at the previous subchapter, an increase of the water level occurs. The level increase is proportional to the fault length. Ward proposes a simple expression for the water level increase (slip) as $Du=2\ 10^{-5}$ L, with Du in km, multiplied by 1000 to have it in m.

Mw	L (km)	W (km)	Du (m)
6.5	28	8	0.56
7	50	14	1.00
7.5	89	25	1.78
8	158	44	3.17
8.5	282	79	5.64
9	501	140	10.02
9.5	891	250	17.83
10	1585	444	31.70

This means that a magnitude 9 earthquake determines an increase of 10 m in the water level.

When the water rises, it is possible to have different patterns (Fig. 3):

- part of the water rises and part decreases
- the water increases in all directions of the same quantity (full rise)
- The longitudinal water distribution can be
- follows a regular pattern (cosinus)
- have a flat pattern

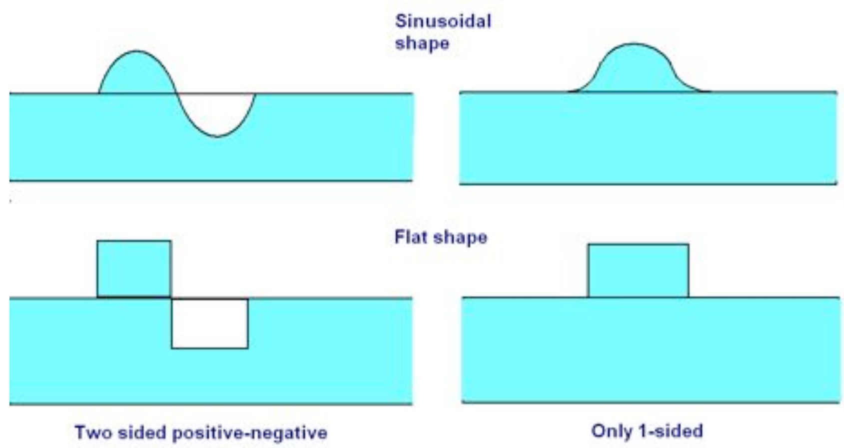


Fig. 3 – Water initial conditions

Any of this type of initial condition will create a different wave pattern in terms of form of the wave. In absence of information on the type of movement of the earth crust, the sinusoidal all positive shape is normally assumed for automatic calculations. It is however possible manually to test any of the other possible solutions.

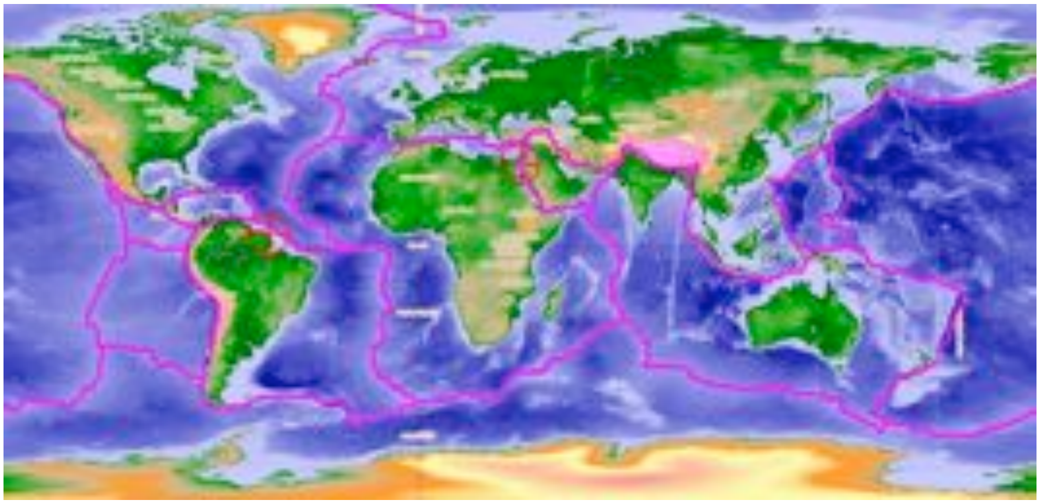


Fig. 4 - Tectonic plates and major fault lines

3.3 Fault direction

The earthquake faults generally occur following existing faults directions, which identify the Tectonic Plates. The known faults lines are indicated in Fig. 4. When an earthquake occurs at a generic location X, Y the programme searches the closer fault line and assigns the fault direction as parallel to that fault line.

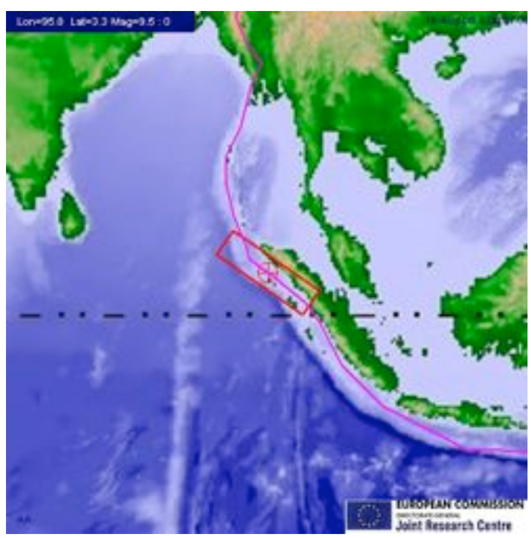


Fig. 5 - Creation of the fault direction and width

In some cases this choice may lead to errors in the correct identification of the fault location. In the case of the Tsunami in the Indian Ocean for instance, the epicenter was in the lower part of the fault and the fault was extending about 1000 km in the north, due to a progressive rupture. This method would instead position the fault symmetrically respect to the epicenter (Figure 5). Few minutes after the event there are no other information to judge the correct position of the fault, therefore this first approximation is the only possible.

3.4 Calculation space initialization

Typically an open ocean Tsunami propagation analysis is performed with a bathymetry grid of 20 min (36 km at the equator); local analyses are calculated with 2 min (1.8 km). Run-up calculations, to evaluate the flooding extent, need to be performed with even higher resolutions (i.e. 150-200 m, or 4.5 to 6 sec). The base bathymetry is the 2 min dataset, known as ETOPO-2. In some areas however the bathymetry has been improved, as in the Caspian Sea, where very coarse data were present.

The programme redefines the bathymetry according to the required cell size. The new bathymetry is obtained interpolating each point using the four adjacent data points. In case an automatic calculation is performed, the programme selects a bathymetry size according to the following logic:

- determination of the fault width and length, as indicated in 0
- evaluation of the maximum cell size, considering that the minimum size (width) has to be represented at least by 10 cells. The width of the calculation as 5 times the fault length but limited to have a maximum grid of 600x600 and thus accordingly determined
- evaluation of the depth at the epicenter and calculation of the wave velocity
- determination of the maximum calculation time considering the wave velocity and the assumed width size

Example: M 7.5 earthquake

Fault length=89 km
Fault width=24 km

$$\text{Max cell size}=\frac{24\cdot 180\cdot 60}{10\cdot \pi \cdot 6340}=1.30\ \text{min}$$

(Earth radius=6340 km)

WidthMax = 7.26 min = 800 km

Assuming a depth of 1460 m, the wave velocity is 431 km/h, thus the maximum problem time is

T= 800/431=1.9 = 1 h 54 min

If the depth is lower, 500 m, the velocity is lower, 252 km/h and thus the problem time longer, 3h 18 min.

Therefore the cell size depends strongly on the magnitude of the earthquake. Greater is the magnitude and greater is the cell size and the calculation domain size.

3.5 Tsunami propagation in the Ocean

It is now interesting to evaluate how the initial height of the Tsunami reduces as it propagates in the ocean. If a Tsunami of initial height H_o propagates from a point source and a constant water depth is considered, the wave amplitude at distance R is proportional to the inverse of the distance and proportional to the initial height (Figure 6).

$$H \propto H_o R^{-1}$$

This means that the height cannot be higher that the initial height and reduces along the distance.

Taking into account the motion equations it is possible to see that the height is initially proportional to a value between 0.5 and 1 (Ward).

In theory using the above correlations to express the wave height reduction as the Tsunami propagates in the ocean.

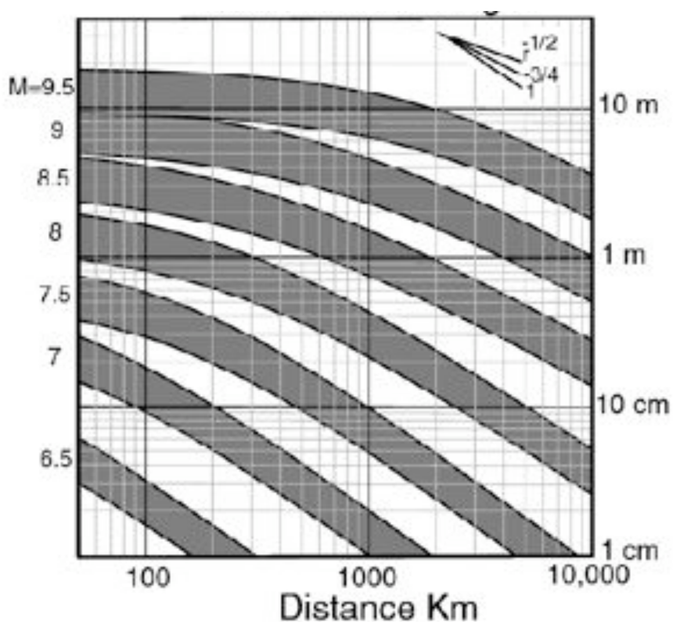


Fig. 6 – Relation between magnitude and height at various distances

However after some attempts to use easy relations as the one above as connected with the wave propagation model, it has been decided to use the complete shallow water equations because there are so many different situations that it is not possible to consider all the variations. A typical example is an isle around which the wave is propagating and in which the term "distance from the epicenter" looses its meaning because is it the distance in straight line or the distance along the path?

3.5.1 Shallow water propagation model

In order to express the Tsunami propagation it is possible to use the shallow water equations in the form proposed by C. Mader coded into the SWAN code (Mader 2004).

The model uses the mass and momentum conservation equations in 2 dimensions, with the approximation of constant velocity along the height. This theory is valid when the ration wave length over the water depth is low. Therefore for Tsunami calculations, considering about 4000 m as maximum depth, when the wave length is several times the depth (i.e. 10 times) so when the wave length is greater than 40 km.

Mass conservation equation

$$\frac{\partial H}{\partial t} + \frac{\partial[(D+H)U_x]}{\partial x} + \frac{\partial[(D+H)U_y]}{\partial y} = 0 \qquad (1)$$

Momentum conservation

$$\frac{\partial U_x}{\partial t} + U_x\frac{\partial U_x}{\partial x} + U_y\frac{\partial U_y}{\partial y} - FU_y + g\frac{\partial H}{\partial x} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + A^{(x)}$$

$$\frac{\partial U_y}{\partial t} + U_x\frac{\partial U_x}{\partial x} + U_y\frac{\partial U_y}{\partial y} + FU_x + g\frac{\partial H}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + A^{(y)} \qquad (2)$$

Where D is the water depth (under water is positive depth, mountains are negative depths), H is the local water level, U_x and U_y are the velocities in the two directions, P is the pressure derivative, which is express as water level difference, and A contain tide generating forces.

The above equations are integrated over control volumes and finite difference equations are obtained. The original code by Mader in Fortran Language has been rewritten in C and connected with a Visual Basic driver into the SWAN-JRC code.

3.6 Identification of relevant locations

In order to identify if a location is hit or not and with which height the following procedure is adopted. At each calculation time step a check of every point of the calculation grid is performed. If the height of the wave is greater than 80% of the depth (h/d>0.8) or if the height is positive and the depth positive (water on the earth), a check is performed of all the locations at a distance of 5 km from the grid center (Fig. 7). These locations are assigned the wave height calculated for that cell. The procedure is repeated for each calculation cell. The database for identifying the locations includes about 700 thousands cities around the world.

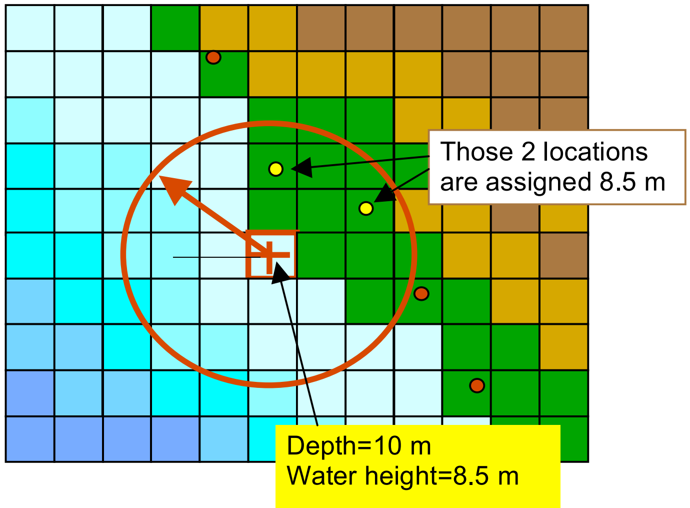


Fig. 7 – Identification of locations

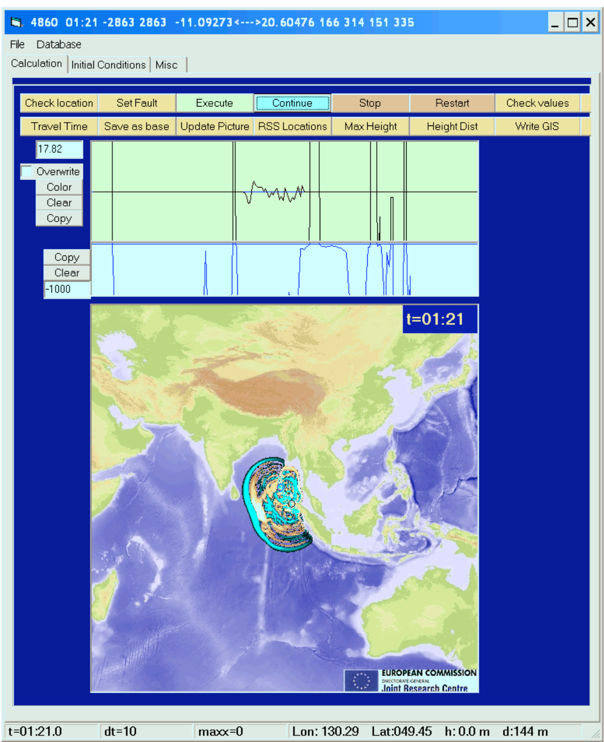


Fig. 8– Calculation output window

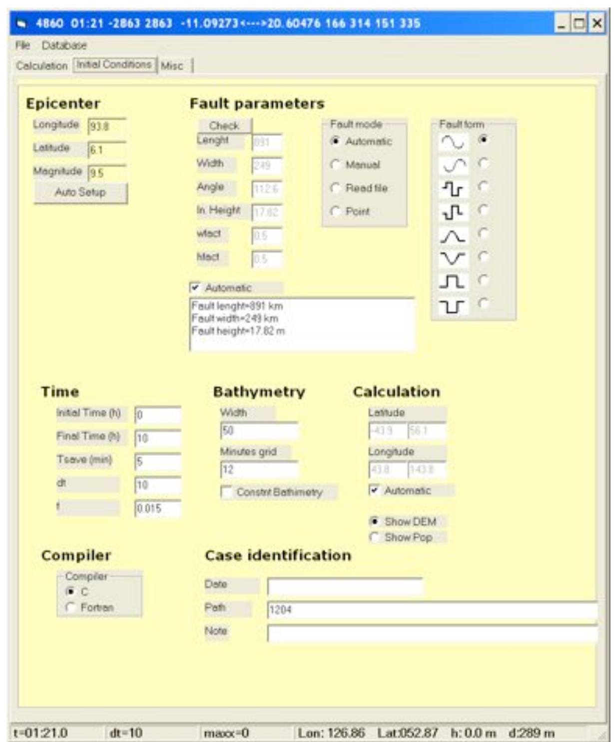


Fig. 9 -User interface to establish the initial conditions of the calculations

3.7 The JRC-SWAN interface

Very often the difficulty to use some computer programmes is represented by the user interface which is difficult to use and not easy to perform several sensitivity analyses. In order to make the programme user friendly a user interface has been developed. This is in the form of a Windows programme which allows establishing and changing all the initial conditions. It is also possible to change the form of the fault and its shape (Fig. 8 and 9 above).

4. JRC TSUNAMI ASSESSMENT TOOL WORKING MODE

The JRC Tsunami assessment tool is part of the Global Disasters Alerts and Coordination System (GDACS), a joint United Nations (OCHA) and Commission (ECHO, ENV, and JRC) system. GDACS does not make physical observation (like deep see observations or seismographs). Instead, it picks up such information though web protocols and performs additional processing such as overlaying information with population density. GDACS aims at controlling the information flow after the disaster, including fast alerts, updated news, satellite maps and needs and relief related information.

When a new event is detected by the seismological sources (USGS, EMSC), an evaluation of the event is performed to estimate the importance of the event from humanitarian point of view. If the event is relevant the system automatically sends out alerts (email, SMS, fax) to the registered users. The information is published on the GDACS web site in real time (Fig 10).

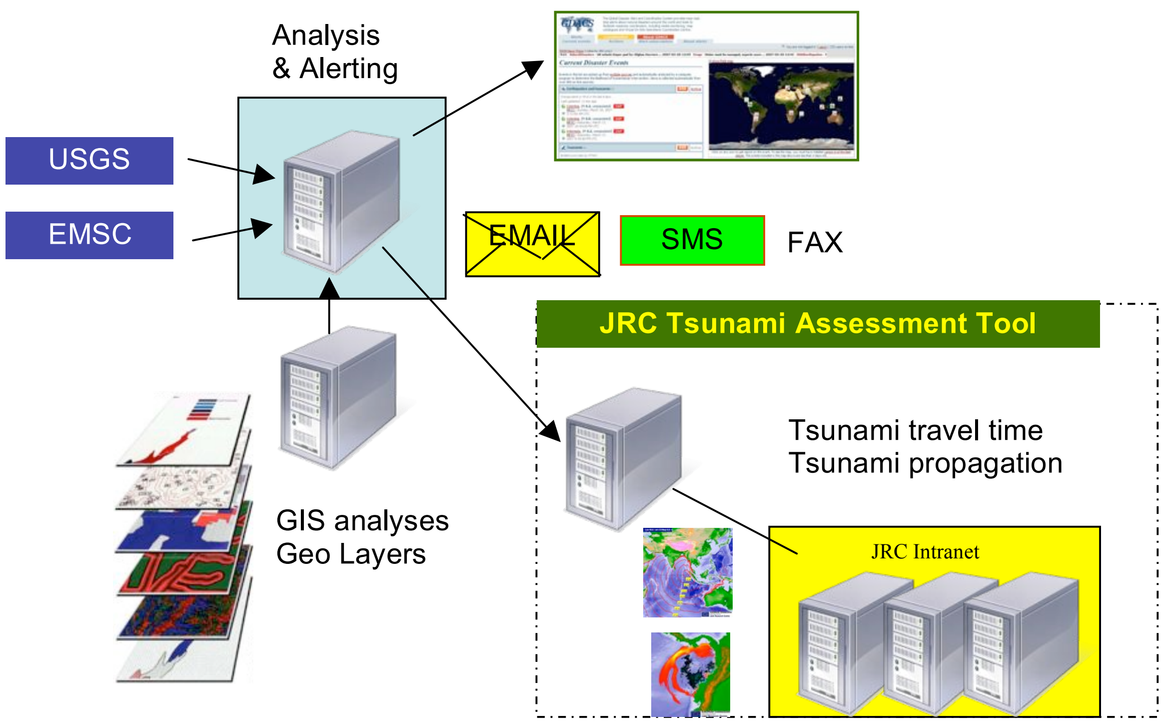


Fig. 8 – Architecture of the Global Disasters Alerts and Coordination System and relation with the Tsunami Assessment

In case of an earthquake event occurring under water and of magnitude greater than 6.5, the JRC

Tsunami Assessment Tool is invoked and a new calculation is requested. The current arrangement foresees 1 collection server and 3 execution server. When a new calculation is to be performed one of the three servers picks up the required initial conditions and begins the calculation. In the meantime the other two servers are in standby, waiting for additional requests. The reasons for multiple execution servers are the following: a) possibility that two events occurs at very short time interval each other and a new calculation is required (on 25/3/2007 two earthquakes in Vanuatu and Japan occurred at 1 min each other); b) events are redefined in terms of position or magnitude and therefore a new calculation should be performed; c) possibility to perform systematic calculations within a range

The calculations are all stored in a database and a file system. This means that if a new calculation is requested with the same parameters of one already present in the database this calculation is offered by the system as result of the analysis. The current settings is that a new calculation is performed if the difference in latitude or longitude or magnitude is greater than 0.1 (degrees or Richer scale value). This is a quite stringent requirement but it allows having exactly the right calculation for the requested case.

The system works with the method of the web service. It means that if a system (GDACS or any other client) needs a calculation for a certain location (ex latitude/longitude 28.86/-19.73, magnitude 8.2), it has to perform a call to a specific Internet address such as:

http://...cmd.asp?CMD=SET_CALC&eqid=LP001&evDate=01/12/2007&**mag=8.2**&**lat=28.86**&**lon=-19.73**&location=off-shore Canary Islands&Client=Manual

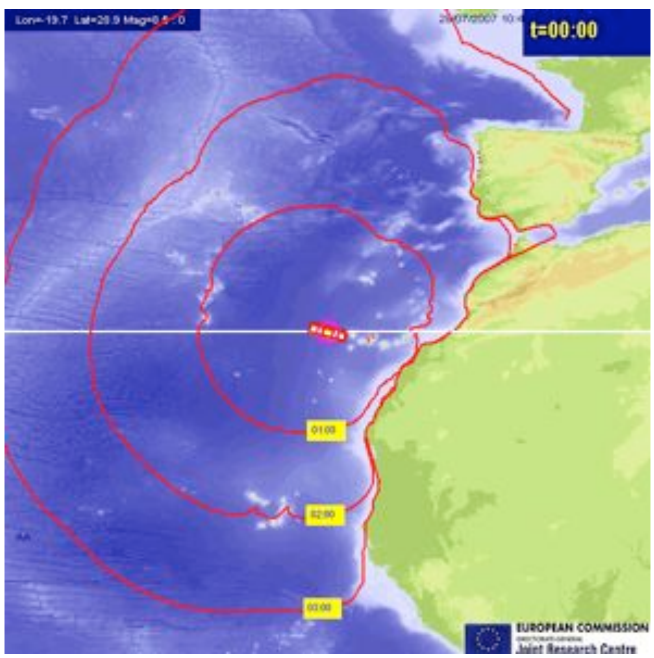


Fig. 9 – Travel time image calculated for the Canary Island case

The system will respond with an xml file containing several information including:
- the initial conditions of the fault (length, width, orientation, height)
- the output parameters:
  - travel time image (Fig. 11)
  - locations where to find the output images and files
  - list of locations affected

If the required calculation is already present in the database because similar to a previous case or already requested by another system, the stored calculation is offered to the user; if not a new calculation is initiated.

Soon after the receipt of the request one of the execution server will start the job and the calculation initiated. About every 5 minutes updates of the running calculation are published at the internet location indicated in the xml response file. Fig. 12 represents the update after 11 min of calculation time. It is possible to note the indication of the locations with the predicted height at each location and the time of the maximum height and the height distribution.

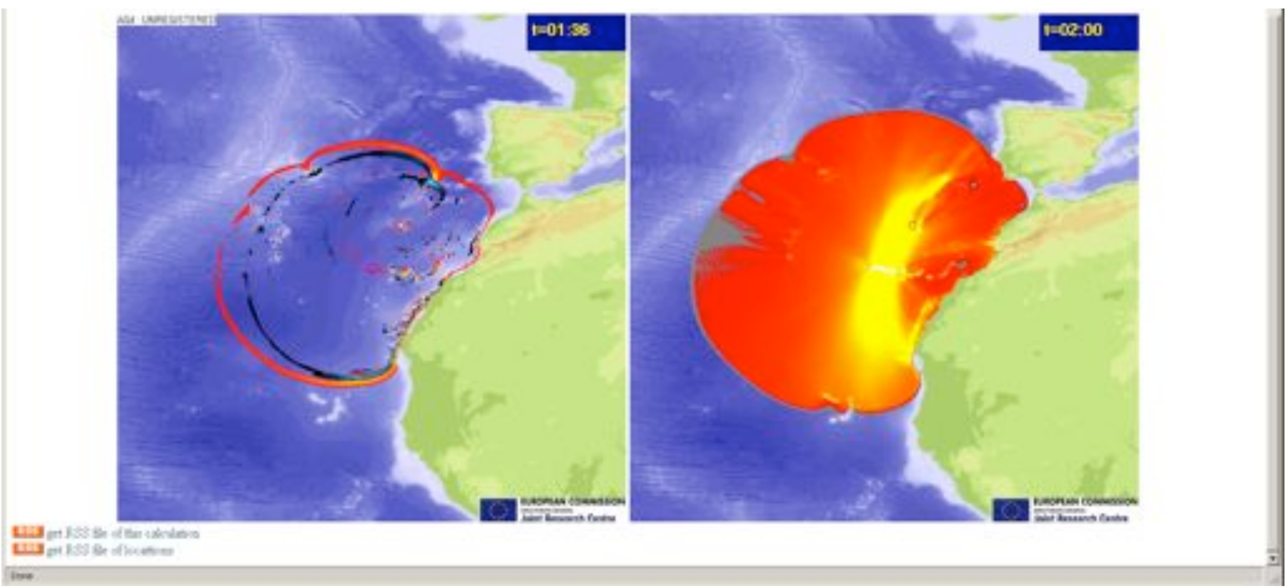
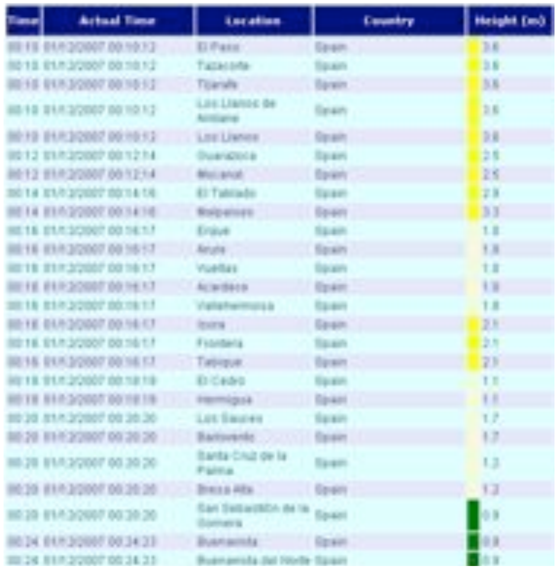


Fig. 10 –Overall output of the JRC Tsunami Assessment System

A typical calculation takes about 30 minutes to be completed. However the closer the location, the quicker it appears in the update page. So, for instance in the case considered above, the location San Sebastian de a Gomera, which is reached in 20 minutes the evaluation takes less than 1 minute; San Pedro da Cadeira (Portugal), reached at 2h 36', is shown after 10 minutes of calculation.

The list of locations with the time after the event and the actual time, the height and the population estimate is updated as soon as the calculation progresses in the model result page (Fig. 13).

The final form of the calculation is indicated in Fig. 14 which shows the maximum height in any location.



Time	Actual Time	Location	Country	Height (m)
00:10	01/12/2007 00:10:12	El Paso	Spain	3.6
00:10	01/12/2007 00:10:12	Tazacorte	Spain	3.6
00:10	01/12/2007 00:10:12	Tijarafe	Spain	3.6
00:10	01/12/2007 00:10:12	Los Llanos de Aridane	Spain	3.6
00:10	01/12/2007 00:10:12	Los Llanos	Spain	3.6
00:12	01/12/2007 00:12:14	Guarazoca	Spain	2.5
00:12	01/12/2007 00:12:14	Mocanal	Spain	2.5
00:14	01/12/2007 00:14:16	El Tablado	Spain	2.9
00:14	01/12/2007 00:14:16	Malpaises	Spain	3.3
00:16	01/12/2007 00:16:17	Erque	Spain	1.8
00:16	01/12/2007 00:16:17	Arure	Spain	1.8
00:16	01/12/2007 00:16:17	Vueltas	Spain	1.8
00:16	01/12/2007 00:16:17	Acardece	Spain	1.8
00:16	01/12/2007 00:16:17	Vallehermosa	Spain	1.8
00:16	01/12/2007 00:16:17	Isora	Spain	2.1
00:16	01/12/2007 00:16:17	Frontera	Spain	2.1
00:16	01/12/2007 00:16:17	Tabique	Spain	2.1
00:18	01/12/2007 00:18:19	El Cedro	Spain	1.1
00:18	01/12/2007 00:18:19	Hermigua	Spain	1.1
00:20	01/12/2007 00:20:20	Los Sauces	Spain	1.7
00:20	01/12/2007 00:20:20	Barlovento	Spain	1.7
00:20	01/12/2007 00:20:20	Santa Cruz de la Palma	Spain	1.2
00:20	01/12/2007 00:20:20	Breña Alta	Spain	1.2
00:20	01/12/2007 00:20:20	San Sebastián de la Gomera	Spain	0.9
00:24	01/12/2007 00:24:23	Buenavista	Spain	0.8
00:24	01/12/2007 00:24:23	Buenavista del Norte	Spain	0.8

Fig. 11 – Detail on the list of locations with indication of locations and population estimates

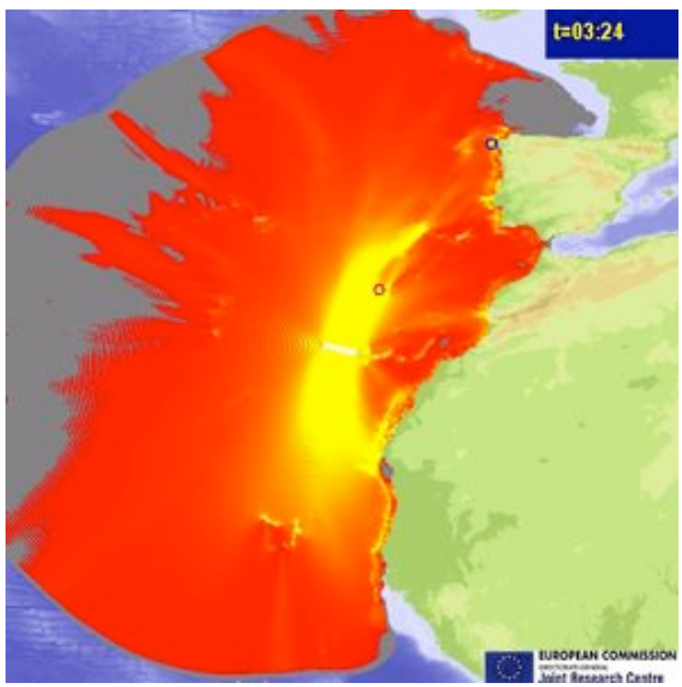


Fig. 12 – Final height distribution for a M 8.2 earthquake occurring off-shore Canary Islands

5. ACTUATIONS OF THE JRC TSUNAMI ASSESSMENT SYSTEM

The Tsunami Assessment Tool is operational since November 2005. Since the start of the operations the actuation of the system was requested 13 times (as 8/8/2007). In 8 cases real Tsunamis were generated, in 3 cases the earthquake depth was too high to generate a Tsunami (>100 km), in 1 case the initial magnitude of 6.9 was then lowered to 5.7, in 1 case there was no tsunami even if the depth was very low (2 km).

#	Location	Magnitude	Depth (km)	Date	CPU time min	Note
1	Kuril Islands	M 8.3	30	15/11/06	22	**0.4 m Tsunami** reached Japan, Hawaii and California
2	China	M 7.2	2	26/12/06	28	No Tsunami generated
3	Kuril Islands	M 8.2	10	13/01/07	40	**Small Tsunami generated**
4	Indonesia	M 7.2	10	21/01/07	22	**Small Tsunami generated**
5	Vanuatu	M 6.9	35	25/03/07	23	**Small Tsunami generated**
6	Japan	M 7.3	50		48	Small Tsunami generated
7	Solomon Island	M 8.1	10	01/04/07	22	**10 m Tsunami**, about 200 persons dead
8	Papua New Guinea	M 6.9[1]	20	01/07/07	25	No Tsunami generated[3]
9	Honshu	M 6.6	55	16/07/07	34	**0.5 m Tsunami** on Japanese coasts, damages from the earthquake
10	Honshu	M 6.8	314	16/07/07	38	No Tsunami generated
11	Vanuatu	M 7.3	144	01/08/07	35	No Tsunami generated
12	Sakhalin	M 6.9	39	02/08/07	30	**0.3 m Tsunami generated**
13	Indonesia	M 7.5	289	08/08/07	60	No Tsunami generated

(Situation as 8/8/2007. New cases occurred after that, as Peru' earthquake, which was correctly calculated)

[1] This earthquake was initially classified 6.9 by GEOFON, finally reduced to 5.7

Therefore assuming no Tsunami below 100 km (a modification done in the last release of the system), and excluding the case of wrong initial magnitude, on 12 cases 11 would have been correctly calculated, which is extremely good result.

An analysis has been done on the time of issuing of the various PTWS bulletins and the execution of the calculations for two events: Kuril Island (15/11/2007) and Solomon Island event (01/04/2007). The reason for choosing these two events is that the first one can be identified as a long distance Tsunami, since traveled up to Japan, Hawaii and California. The second one is instead a more localized event.

5.1 Kuril Island event, 15/11/2006

On 11/15/2006 11:14:01 AM UTC an earthquake of magnitude 8.3 struck the unpopulated Kuril Islands between Russia and Japan (Lon: 153.22 Lat: 46.68). The earthquake triggered a relatively small tsunami (with wave heights up to 50cm), which reached mainly Japan, Russia but it was detected also in Hawaii, California coasts and South America. No casualties were reported.

Calculations of tsunami wave height were automatically initiated with the JRC SWAN model. Results were updated on the dedicated web site every 10 minutes. The model predicted a maximum height of 40 cm in Japan arriving at 1h 30 min; in effect a wave of about 30 cm arrived at 1h 22 min, according to Japanese measurements (Fig. 15).

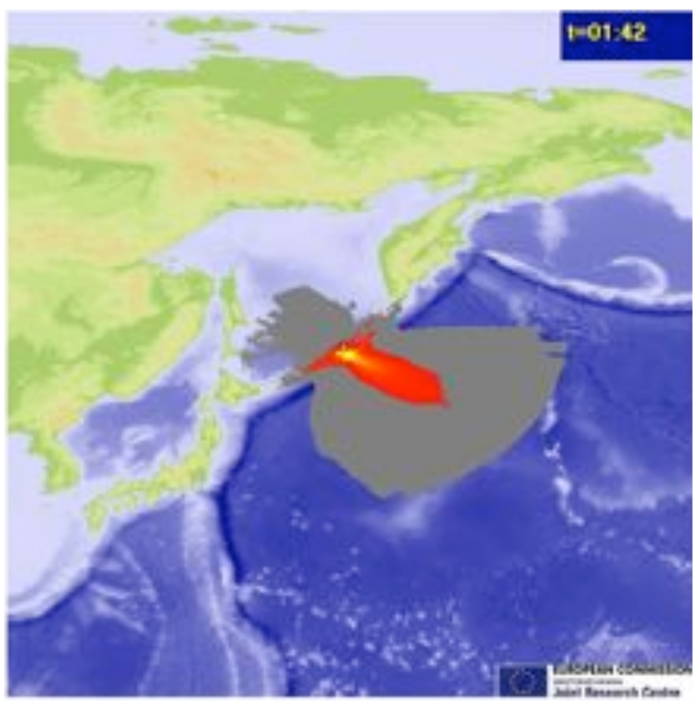


Fig. 13 – Height Distribution for the Kuril Island event of 15/11/2006

The highest predicted height was 6.6 m to occur on the inhabited Islands (Fig 16).

The calculation, initiated when the notification occurred, 17 min after the event, and was completed in 30 min thus, related to Japan, there were still 43 minutes available for early warning.

This is the timeline of the events actuation

0	11:14:15 UTC M7.7 earthquake Kuril Islands
16’	1st PTWS message generated (“**it is not known if a Tsunami was generated**”, arrival times indicated)
17’	JRC-SWAN calculation starts
47’	JRC-SWAN calculation ends, locations identified with 0.4-0.5 m height maximum
1h	Magnitude revised to M 8.1 2nd PTWS message generated (“**it is not known if a Tsunami was generated**”)
1h 1’	New JRC-SWAN calculation started
1h 16’	JRC-SWAN predicts Hokkaido, Japan reached 0.1 m at 1:30
1h 22’	JRC-SWAN predicts Oishi, Japan, reached at 2 h, 0.12 m
1h 30’	Hasahi Hokkaido reached by the wave, 0.3 m
2h 3’	3rd PTWS bulletin, indicating that “**a Tsunami was generated**” and that two locations in Japan were reached by the wave
3h 44’	4th PTWS bulletin, indicating that also Alaska was reached by the wave, 0.2 m

The image below was produced at the end of the first calculation, when the known magnitude was 7.7. Already this image was showing very clearly that the direction of the energy distribution was such that a major wave on Japan had not to be expected.

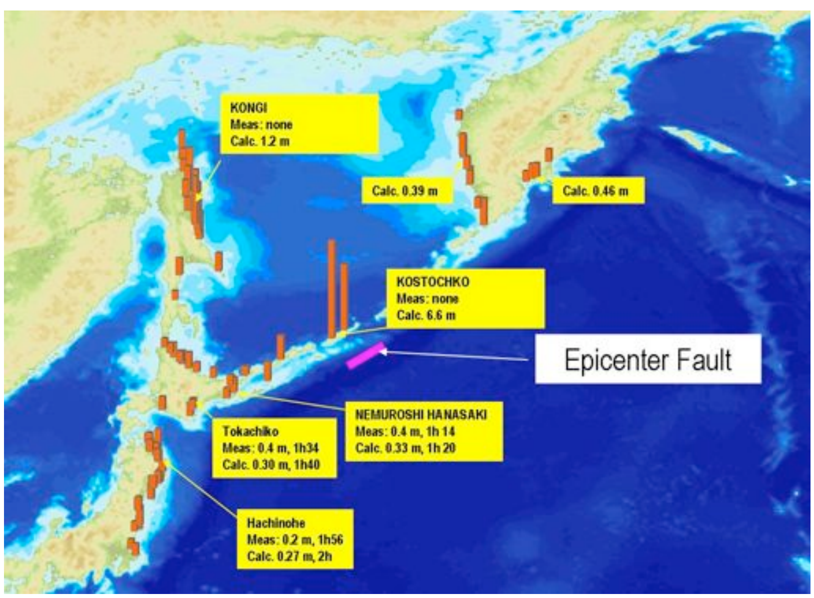


Fig. 14 – Distribution of the predicted and measured after the Kuril Island event of 15/11/2006

Also the image indicates that great amount of energy is directed towards Hawaii, which indeed were reached several hours after by waves up to 1 m.

The results of the revised calculation are indicated in the figure below, which shows the various locations reached by the wave. It is interesting that one remote location (Kostochko) was reached by a 6.6 m wave. Analysis of the satellite images in the area allowed concluding that indeed an important wave reached those coasts (Fig 17).

The analysis of this event indicates that in this case of long distance Tsunami the information was produced rather quick, well in advance respect to the time the wave reached the first populated areas (Japan). The timings are comparable with the ones of PTWS. The use of these calculations could have allowed issuing bulletins indicating that no major problems were expected on Japanese coasts.

Fig. 15 - Satellite image on the coast on Kuril Islands showing that a section of the vegetation was taken out as a result

5.2 Solomon Island Event

On Sunday 1 April 2007 at 20:39 UTC, an underwater earthquake of magnitude 8.1 caused a tsunami of several meters to hit the Solomon Islands. More than 10 people have been reported killed and thousands affected or injured. The international community was put on standby and offered help through OCHA. Australian beaches were evacuated.

JRC systems detected the event 16 minutes after the event, i.e. as soon as it was published by the

United States Geological Survey. The event was calculated to be a Red Alert and over 3000 alerts were sent out.

0	20:40:00 UTC M7.7 earthquake Solomon Islands
15’	1st PTWS message generated (“**it is not known if a Tsunami was generated**”, arrival times indicated)
16’	JRC-SWAN calculation starts with 7.7 magnitude
17’	JRC-SWAN identified the following locations in less than 1 minute of calculation: Hofovo, 3.2 m, Harai 3.1 m, Vanikuva 3.1 m, Judaea 3.1 m, Au 3.1 m, Kunji 3.3 m, Pienuna 1.5 m, etc. All these locations are calculated to be hit in less than 5 min.
41’	JRC-SWAN calculation completed, calculated values: Harsi 1.9 m, Vanikuva 2.2 m, Kunji 1.5 m, Honiara 0.1 m (predicted to be hit at 54’) etc
52’	2nd PTWS message generated (“**it is not known if a Tsunami was generated**”, arrival times indicated), revised magnitude to **8.1**
53’	Second JRC-SWAN calculation initiated
54’	JRC-SWAN new estimates of locations in less than 1 min: Ganongga 3.5 m, Pienuna 3.5 m, Mundimundi 1.8 m, Paramata 1.8 m, Iringgila 1.4 m, Lunga 1.6 m, Vella Lavella I 1.5 m, Eghelo 3.7 m, Mburuku 3.7m etc.
57’	Honiara reached by 0.15 m wave (measurement)
1h 5’	Second JRC-SWAN calculation (with higher magnitude) completed (Honiara predicted to be reached at 48’ with 0.3 m)
1h 59’	3rd PTWS message, confirmation of the Tsunami, measurements in Honiara reported (0.15 m, at 57’)

Other 5 PTWS messages follow with additional locations measurements, but none of these indicate high wave values (Manus 9 cm, Vanuatu 15 cm, Cape Ferguson 11 cm) because the measurement locations were not close to the epicenter and not in line with the greater energy track (see the orange dots in Fig. 18).

The JRC-SWAN calculations were available already at least at the time of the second PTWS message, indicating about 3.3 m in Kunji. Thus the availability of this calculation tool could have been useful in identifying the extent of the possible affected areas, once the tsunami would have been confirmed by the far measurement points.

It is interesting to note that, although the first PTWS message was issued 15’ after the event, the email was received at JRC only after 2h 31’. At least one media source reported that the GDACS alert arrived while the Pacific Tsunami Warning Centre did not issue any alert message[2].

[2] MICHAEL FIELD - Fairfax Media, initially wrote: “The Pacific Tsunami Warning Center in Hawaii has not issued any warnings but the European Union/United Nations Global Disaster Alert and Coordination System says a tsunami is a high risk. ”. The text of the article was then modified.

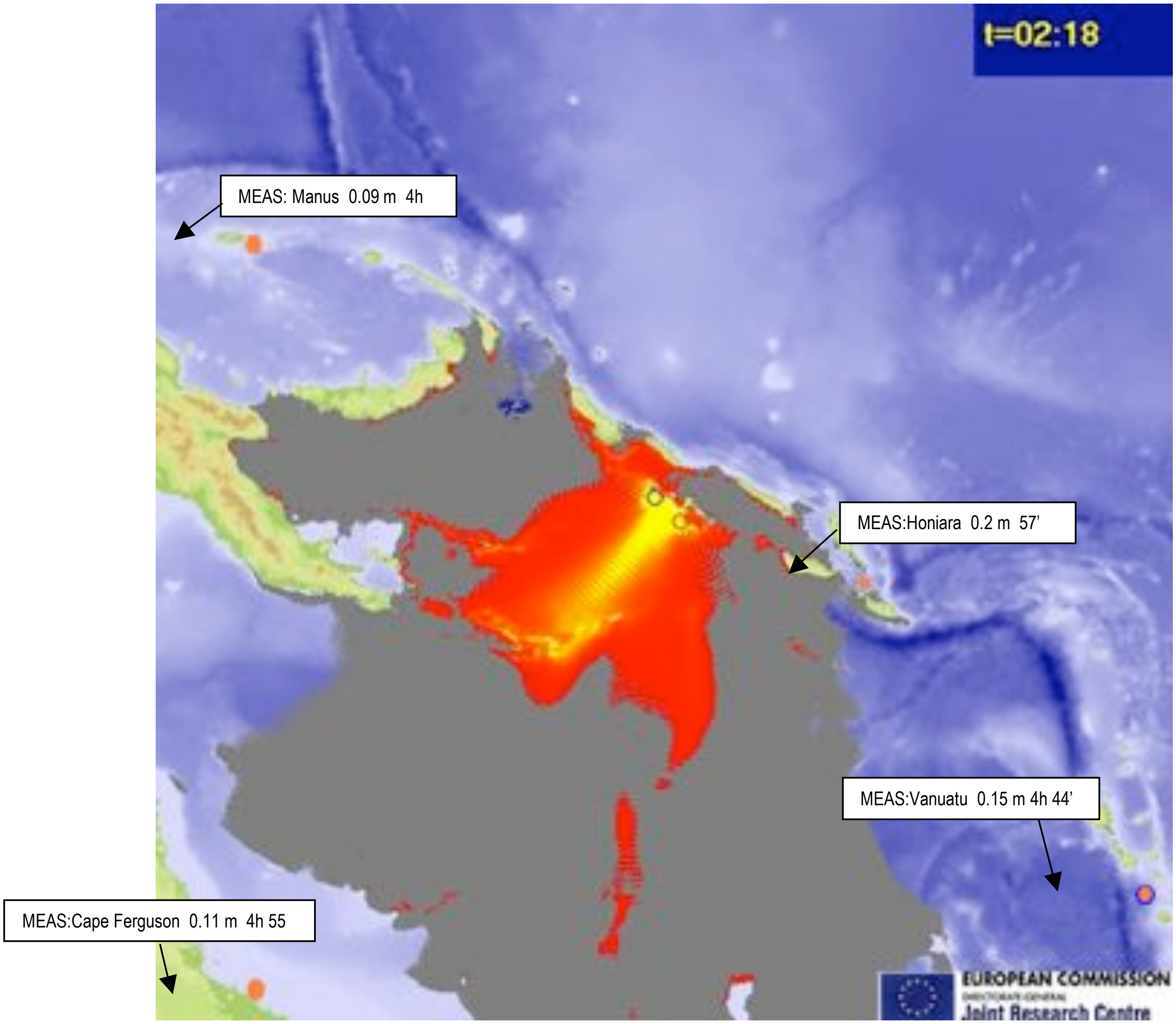


Fig. 16 – Solomon Island Event. In orange the positions of the water height measurements indicated in the PTWS messages

6. FUTURE ACTIVTIES

Is it better to use on-line calculations performed when an event occurs or pre-calculate all the possible conditions?

On-line calculations have the advantage that it is possible to specify the exact conditions (lat/long and magnitude; then it is possible to upgrade the model without the need to re-run all the thousands of calculations.

Another argument in support to the on-line calculation is the fact that the computer speed increases constantly over the years. In the last 5 years the computing power increased by a factor greater than 10 (Fig. 19). This means that in 5 years from now it could be possible to perform in 3 minutes the same calculation that now is performed in 30 minutes!

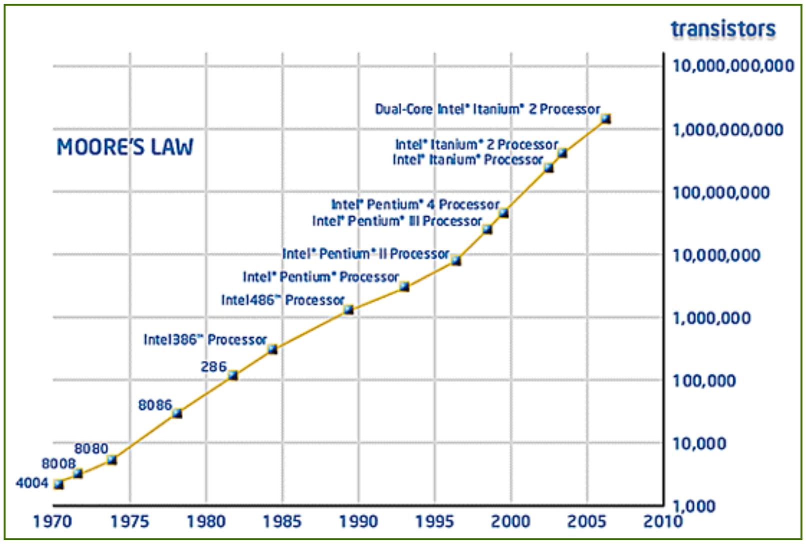


Fig. 17 – Calculation speed over the years

A disadvantage of the on-line calculation is that the system must be ready to execute the calculations at any time. The failure probability should be reduced as low as possible by adopting a number of execution servers. At the moment we are using three servers but we intend to increase them to five.

The pre-calculation has the advantage to have already all the calculations performed thus allowing more time for the alerting. However it is not possible to make any possible calculation for the whole world. In order to reduce the amount of needed calculations to the areas really potentially tsunami prone, a reduced calculation grid has been defined. For every historical Tsunamis source (each square in Fig. 21), the bounding 5x5 grid points have been determined using a 0.5 degrees grid.

This produces an overall not-uniform grid of 10185 data points as initial earthquake location. Considering that each calculation imply 30 minutes CPU time and 8 Mbytes storage space, means to spend 1 month on 7 computers and occupy 80 Gbytes per set of magnitude calculation. Calculating from M 6.5 to M 9.5 every 0.25, that means 12 sets of magnitude calculations (1 year using 7 computers). We started these grid calculation and when completed will be used in the normal routine operations.

Therefore the solution that we find more adequate is, at the moment of the event to provide an initial estimate based on the grid calculations we are creating, using the closer initial point on the 0.5 grid database and in the meantime launch a more precise calculation based on the actual location and magnitude, which will be ready, as it is currently, within 30 minutes.

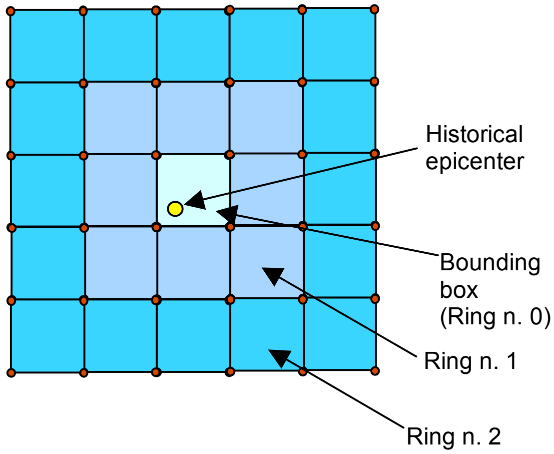


Fig. 18 – Definition of the grid boundary for historical Tsunamis

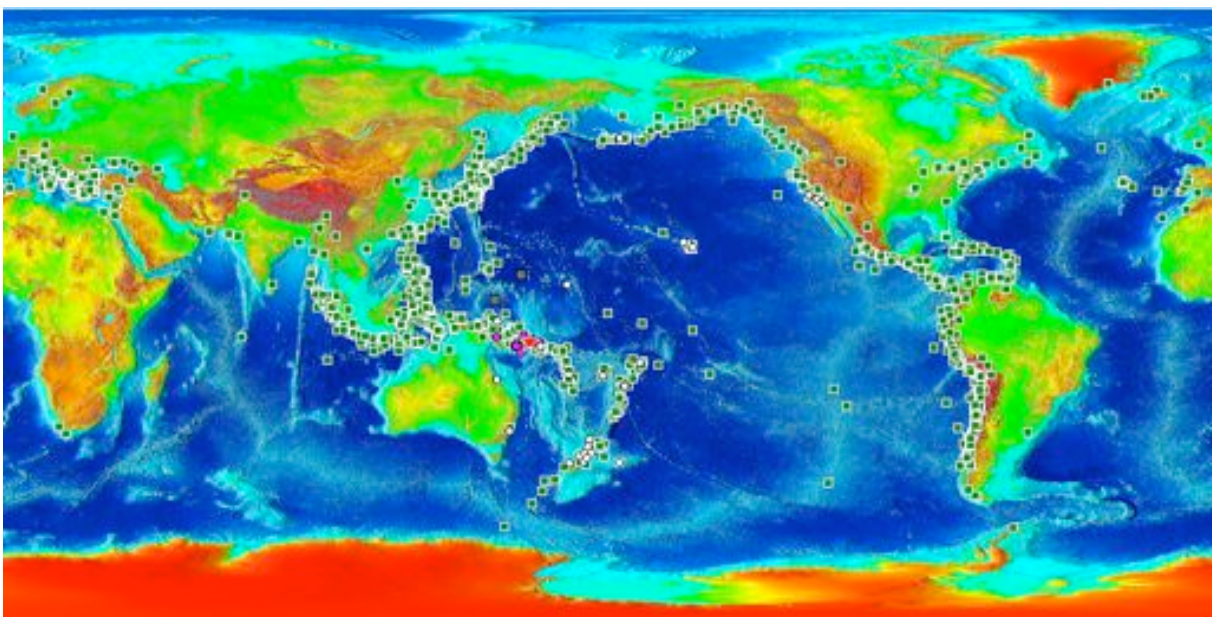


Fig. 19 - Historical database of Tsunami in the world (source NOAA, NGDC database)

7. CONCLUSIONS

Several computer codes for simulating the Tsunami behavior have been developed worldwide. None of them however has been designed in order to respond automatically with the only available information known few minutes after an earthquake event which may cause a Tsunami and publish, while it is running, the results on the web.

The JRC Tsunami Assessment Modeling System is a complex series of computer codes, procedures and computers set-up to respond in about 30 minutes to any request coming from Early Warning Systems, such as the Global Disaster Alerts and Coordination System (GDACS) or the LiveMon[3], both developed and operated by JRC.

The Tsunami Assessment System is now fully operational and performs automatic calculations whenever receives requests from the early warning systems.

In the future the system will be powered with a pre-calculated set of grid calculations to reduce the response time. The calculation time to produce such a database is quite large (1 year) but it will allow saving important time during the real events.

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IMPACT OF TSUNAMI 2004 IN COASTAL VILLAGES OF NAGAPATTINAM DISTRICT, INDIA

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ABSTRACT

A quake-triggered tsunami lashed the Nagapattinam coast of southern India on December 26, 2004 at around 9.00 am (IST). The tsunami caused heavy damage to houses, tourist resorts, fishing boats, prawn culture ponds, soil and crops, and consequently affected the livelihood of large numbers of the coastal communities. The study was carried out in the Tsunami affected villages in the coastal Nagapattinam with the help of remote sensing and geographical information science tools. Through the use of the IRS 1D PAN and LISS 3 merged data and quick bird images, it was found that 1,320 ha of agricultural and non-agricultural lands were affected by the tsunami. The lands were affected by soil erosion, salt deposition, water logging and other deposited sediments and debris. The maximum run-up height of 6.1 m and the maximum seawater inundation distance of 2.2 km were observed at Vadakkupoyyur village in coastal Nagapattinam.

Pre and Post Tsunami survey on soil quality showed an increase in pH and EC values, irrespective of distance from the sea. The water reaction was found to be in alkaline range (> 8.00) in most of the wells. Salinity levels are greater than 4 dS m^{-1} in all the wells except the ring well. The effect of summer rainfall on soil and water quality showed the dilution of soluble salts. Pumping of water has reduced the salinity levels in the well water samples and as well as in the open ponds. Following the 2004 event, it has become apparent to know the relative tsunami hazard for this coastal Nagapattinam. So, the Tsunami hazard maps are generated using a geographical information systems (GIS) approach and the results showed 20.6 per cent, 63.7 per cent and 15.2 per cent of the study area fall under high hazard, medium hazard and low hazard category respectively.

Keywords: Tsunami 2004, impact, run-up levels, soil and water quality, hazard map

1. INTRODUCTION

A Tsunami on 26th December, 2004 by an earthquake of magnitude M 9.0 occurred along the plate boundary marked by subduction zone between the Indian plate and the Burmese micro plate near Sumatra Island of Indonesia with the epicenter located on the shallow depths of seabed (USGS, 2004). Tsunami is a Japanese word which translates as “harbor wave”, now used internationally, refers to a series of waves traveling across the ocean with extremely long wavelength at an average speed of 800 km/hour in the open ocean. As it approaches the coast, the near shore bathymetry significantly increases the wave height resulting in inundation of low lying areas along the coast resulting in mass destruction and in many instances loss of life. Tsunami waves hit the Andaman and Nicobar group of islands within few minutes. The Tsunami waves hit Indonesia, Andaman and Nicobar islands, parts of East coast of India, Thailand, Sri Lanka, Maldives and West and East Africa. The Survey of India reported that the Tsunami hit Cuddalore at 08.00 a.m. (IST), Chennai at 08.40 a.m. (IST), and Paradip, Machillipatanam, Nagapattinam and Vishakhapatnam at 09.00 a.m. (IST) (Navalgund, 2005). In India, the states of Tamil Nadu, Andhra Pradhesh and the Union territory of Andaman and Nicobar islands were the worst affected by the impact of Tsunami. The states of Kerala and the Union Territory of Pondicherry were also affected. Among the different districts in Tamil Nadu, Nagapattinam is one of the worst affected districts by the Tsunami.

The Tsunami 2004 generated by the earthquake killed approximately 275,000 people, making it one of the deadliest disasters in modern history. Beyond the heavy toll on human lives, the Indian Ocean earthquake has caused an enormous environmental impact. It has been reported that severe damage has been inflicted on ecosystems such as mangroves, coral reefs, forests, coastal wetlands, vegetation, sand dunes and groundwater. Tusnami has lead to poisoning of the fresh water supplies and the soil by salt-water infiltration and deposit of a salt layer over arable land. The terrain coastal regions of India affected by the Indian Ocean Tsunami are mostly flat with few mountains. Remote sensing provided a great support during the disaster to get a preliminary idea on the damages caused by Tsunami. Here, the remote sensing and GIS tools were used to identify the extent of seawater intrusion and to estimate the land use and land cover changes.

2.0 STYDY AREA

The study was conducted in Nagapattinam district of Tamil Nadu State, India, which is bounded on the north by Cuddalore district, south by Palk Strait, east by Bay of Bengal and west by Thiruvarur district. The study area falls under fifteen revenue villages Nagapattinam and Kivalur taluks of Nagapattinam district, covering an area of 10,380 hectares. The area lies between 10^{o} 34’32.69” and 10^{o} 46’57.77” N latitude and between 79^{o} 47’02.29” and 79^{o} 51’38.24” E longitude (Fig. 1).

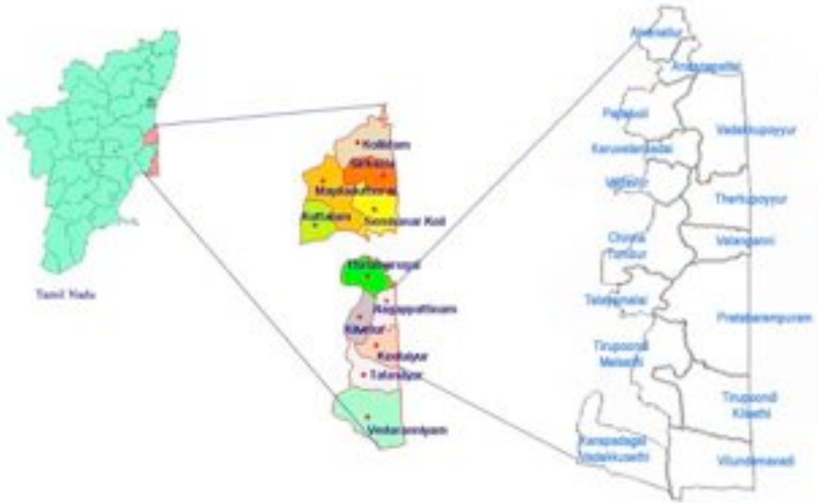


Figure 1. Location map of the study area

2.1 Geology

The geology of the study area comprises of both riverine and marine alluvial deposits. The alluvial deposits of the river Cauvery and its tributaries lie over the Tertiary sandstone. They consist of sands, gravelly sands, clays and sandy clays. The thickness of these formations ranges from 30 m to 400 m. The tidal deposits of Bay of Bengal is invariably seen up to 5 km range from the sea which consists of fine to coarse sand, sandy clays with marine features like shells.

2.2 Climate

The climate is semi-arid. The area receives a mean annual rainfall of 1,337 mm out of which 201 mm (15.03%) is contributed by Southwest monsoon and 921 mm (68.89%) by Northeast monsoon. The mean annual temperature is 28.79¼C and the mean maximum and mean minimum temperatures are 32.66¼C and 24.91¼C respectively.

2.3 Crop cultivation

Rice is grown during November-February rainy season. Large areas are under vegetable crops viz., brinjal, bhendi, chilly, cucumber, melons, gourds and groundnut besides coconut and mango. Fruit crops like mango, cashew, guava and sapota are also raised.

3.0 METHODOLOGY

3.1 Tsunami Damage Assessment

Extent of sea water inundated area, damage to agricultural fields, settlements, salt and other sediment deposition are visually interpreted using Pan sharpened Multispectral data of Quickbird sensor dated 31th December 2004 with a spatial resolution of 70 cm and compared with IRS 1D PAN and P6 LISS3 merged data (Date of pass 21-05-04 (PAN) and 04-06-04 (LISS3)) of spatial resolution of 5.8 m, to get a preliminary idea on the damages caused due to Tsunami occurred on December 26, 2004.

3.2 Land use and Land cover change detection

The land use and land cover changes due to Tsunami were studied using the IRS 1D PAN + P6 LISS3 (before Tsunami) merged data and Quickbird sensor (after Tsunami). The land use of the area were visually interpreted and digitized under ARC GIS 9.0 software. The digitized maps were ground verified and classified. The classified land use map of before and after Tsunami was intersected under Overlay module in the Analysis tool of Arc toolbox. The changes in area between land uses of before and after Tsunami were then extracted from the attribute data.

3.3 Impact of Tsunami on soil and water quality

The soil and water samples were collected after the incident of Tsunami (December 2004) and also after summer rainfall (March 2005) from the same fields where studies were previously conducted for

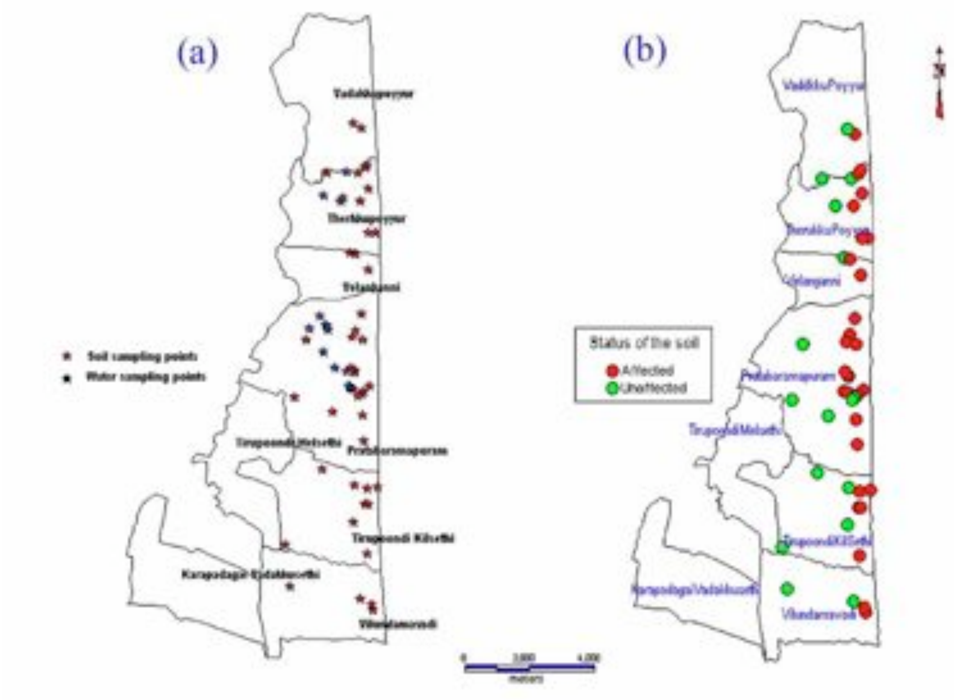


Figure 2. (a) Location of soil and water sampling points (b) Tsunami affected/unaffected points

the assessment of soil and water quality. Totally seventeen soil samples were collected at two different depths viz., 0-15 cm and 15-30 cm from the affected places ranged from 100 – 800 meters from the sea. Six representative water samples were collected from different sources viz., skimming well, ring well and open pond.. The Fig.2 shows the location of soil and water sampling and Tsunami affected and unaffected points, respectively. The soil and water samples were analyzed for pH and electrical conductivity as per the standard procedures.

3.4 Tsunami hazard mapping

Tsunami hazard maps were generated using GIS approach to depict the relative Tsunami hazard of coastal Nagapattinam. In contrast to previous mapping efforts that utilize a single line to represent inundation, hazard is displayed gradationally. A surface is constructed to represent this hazard. From the vicinity of sea about a wide strip of land 2 km area was considered for the study. A line was digitized to separate the sea and inland area. From the margin of sea, 2 km buffer line was created using buffer tool in GIS analysis. Criteria for each hazard zone were chosen in relation to elevation and attenuation. Three-arc second (90 m) resolution Digital Elevation Model (DEM) of Shuttle Radar Topographic Mission (SRTM) was used for elevation control and generation of elevation contours. Criteria boundaries were used to separate regions of varying hazard. Criteria boundaries defined by Patton and Dengler, (2004) were adopted to delineate the regions (Table 1). Zones were constructed

Table 1. Hazard area boundary criteria are initially defined for each zone based on elevation

Zone	Description	High	Moderate	Low	None
Open Coast	Everywhere within 2 km of coast	0-3 m elevation	3-10 elevation	10-35 m elevation	Above 35 m elevation
Coastal Estuary	Low lying flat topography of river valley and bottom lands within 2 km of coast	0-1.5 m elevation	1.5 – 6 m elevation	6-15 elevation	Above 15 m elevation
Bay lands	Low-lying flat topography adjacent to coastal estuary within 2 km of coast	0-1.5 m elevation	1.5 – 3 m elevation	3-5 elevation	Above 5 m elevation
Low-lying uplands	Low-lying flat topography within 2 km of coast	0-3 m elevation	3 – 7.5 m elevation	7.5 – 20 m elevation	Above 20 m elevation
Uplands	All other areas inland of open coast zone above 2 km of coast	Not applicable			

to further adjust the criteria with respect to a physically determined variable hazard. Hazard was displayed as a continuous gradational color scale ranging from high hazard through medium, low to no hazard. The maps were produced in GIS format to facilitate ready adaptation by planners and emergency managers. The methodology adopted for preparation of Tsunami hazard map is given in Fig. 3.

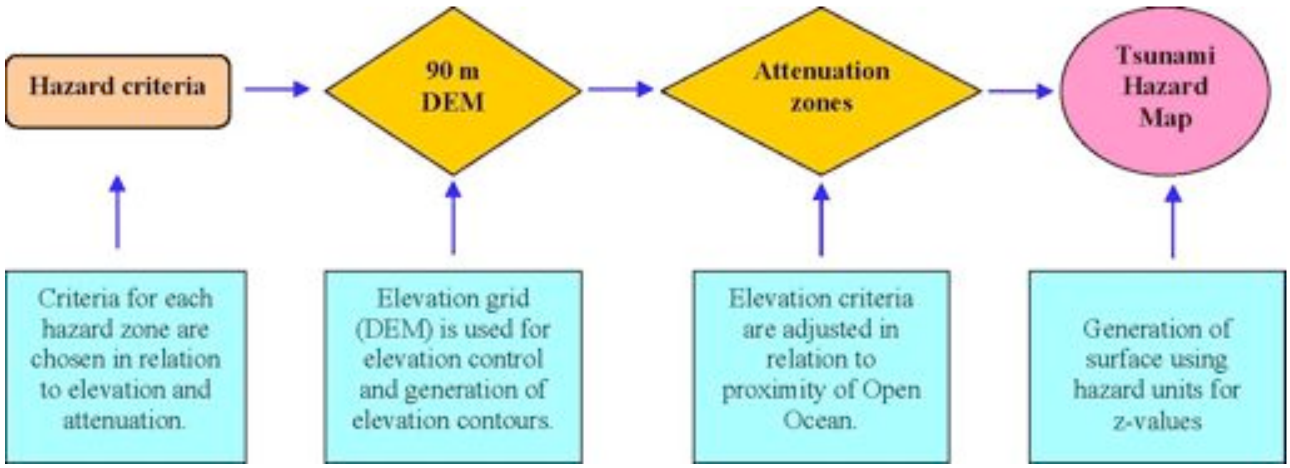


Figure 3. Flow chart showing the process for generation of tsunami hazard map (*Methodology source: Patton and Dengler, (2004)*).

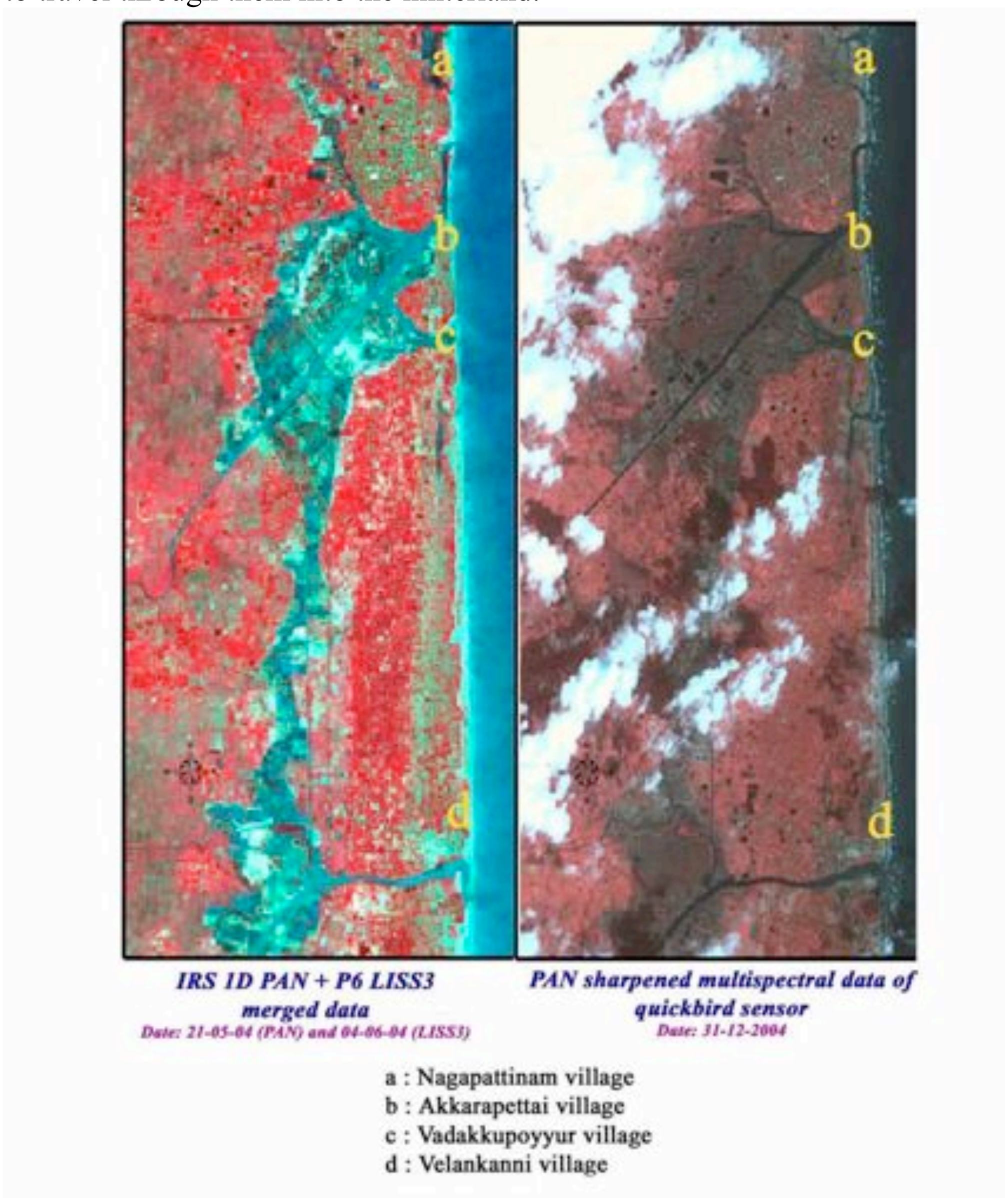
4.0 RESULTS AND DISCUSSION

4.1 Visual discrimination of satellite data

In Nagapattinam district, there are dense households from the coast up to 1.5 km. Tsunami has devastated the Nagapattinam area with a death toll of 6065 people and damaging as many as 40,000 houses (Source: www.tn.gov.in, dt. 14th Feb. 2005) Complete and partial destruction of buildings in Akkarapettai and Keechankuppam villages are clearly visible in the imagery (Fig. 4-9).

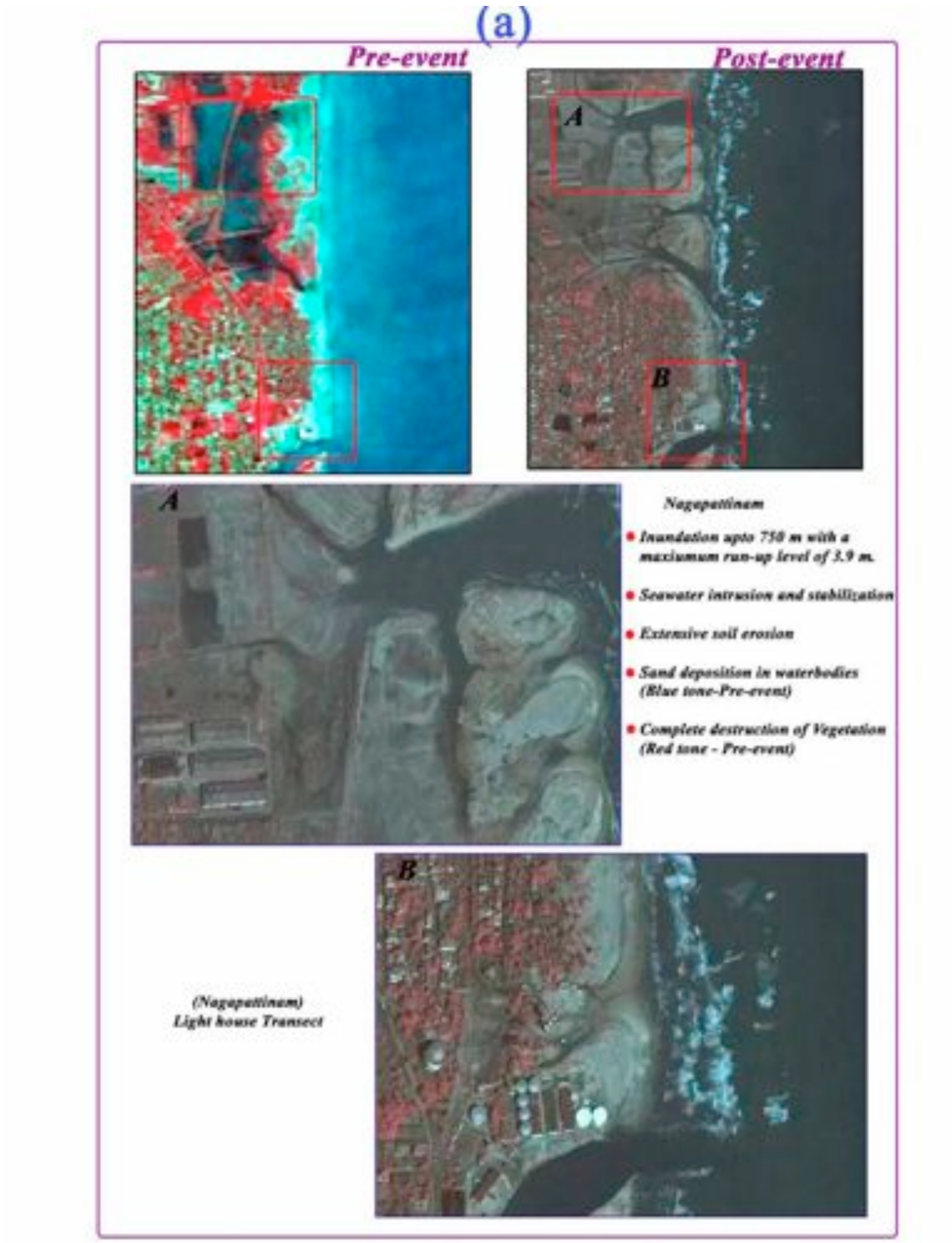
Satellite data indicate that Nagapattinam, Vadakkupoyyur, Therkupoyyur, Keechankuppam, Akkaraipettai, Velankanni, Seruthur, Pratabaramapuram, Tirupoondi Kilsethi and Vilundamavadi are the affected villages in Nagapattinam and Kivalur taluks of Nagapattinam district. The worst affected Nagapattinam (light house transect) showed longer penetration of seawater (750 m) up to an elevation of 3.9 m due to the gentle slope of coastal land combined with the effect of Tsunami wave (Table 2). Presence of creeks like Vedaranayam and Velankanni canal in Vadakkupoyyur and Seruthur village facilitated the seawater inundation up to 2.2 km and 1.95 km up to an elevation of 6.1 m and 5.6 m, respectively. In Velankanni village, the lands interrupted by streets and buildings and open beach led to the penetration of sea water up to 950 m with the maximum run up level of 4.3 m. Coastal lands with heavy plantation and sand dunes in Therkupoyyur, Pratabaramapuram and Tirupoondi Kilsethi. villages showed a sea water intrusion level of 250 m, 282 m and 528 m and up to an elevation level of 4.6 m, 3.3 m and 5.0 m respectively.

The inundated limit shows the vulnerability of the Nagapattinam district of the Tamil Nadu coast due to its flat topography. From the satellite data it was clearly inferred that the regions where the land unprotected by coastal dunes had higher inundation levels compared to places where the coast is protected by dunes. Also, wherever there are openings in the dunes (either due to anthropogenic activity or due to other reasons), inundation was higher as these openings provided a gateway for the water mass to travel through them into the hinterland.



Source: IRS data- NRSA Data centre, Hyderabad; Quickbird data: Pacific-Disaster centre

Figure 4. Visual interpretation of Tsunami affected area of Nagapattinam and Kivalur taluks using remote sensing data

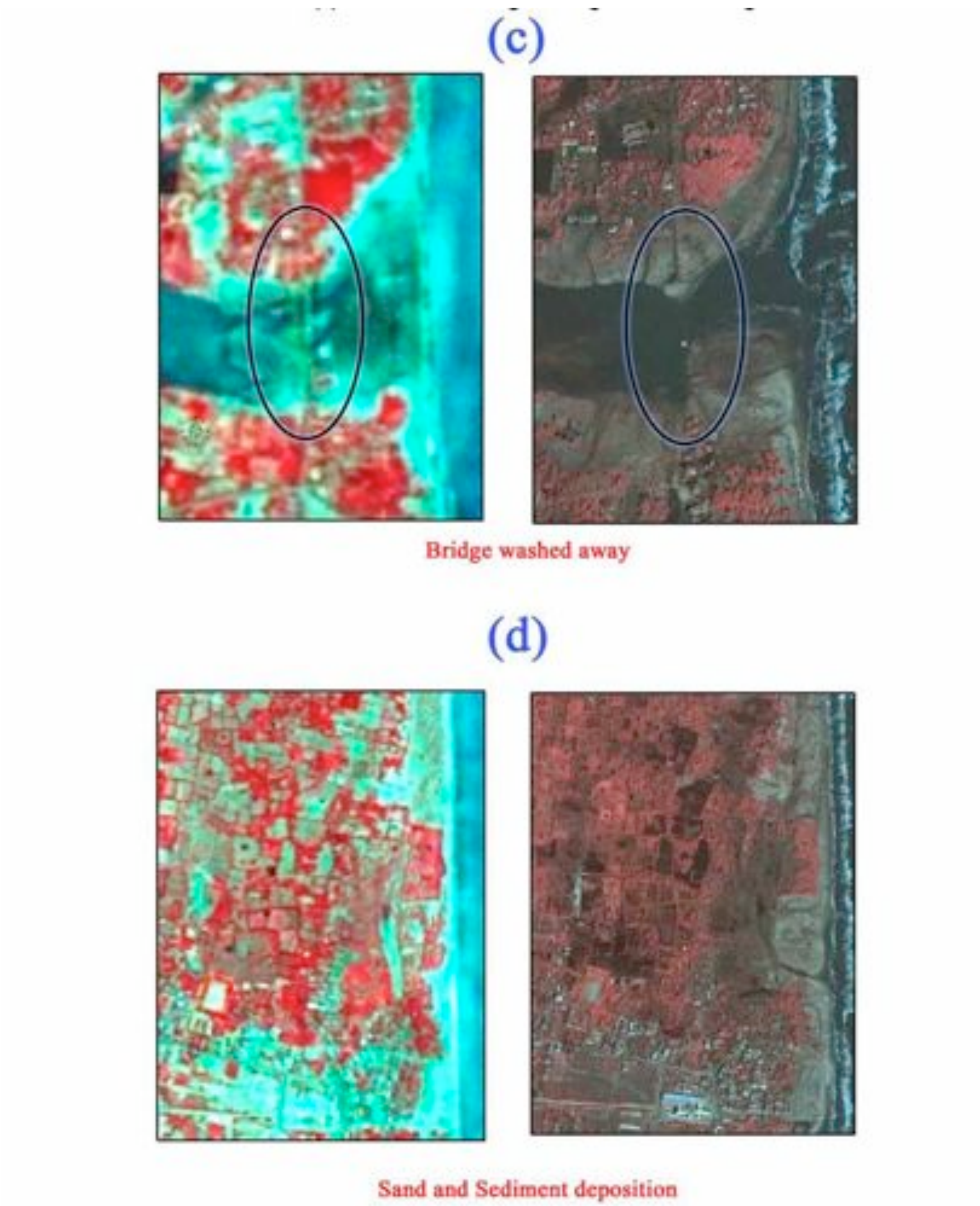


Source: IRS data- NRSA Data centre, Hyderabad; Quickbird data: Pacific-Disaster centre

Figure 5. Visual interpretation of Tsunami affected area of Nagapattinam village using remote sensing data

Source: IRS data- NRSA Data centre, Hyderabad; Quickbird data: Pacific-Disaster centre

Figure 6. Visual interpretation of Tsunami affected area of Akkaraipettai village using remote sensing data



Source: IRS data- NRSA Data centre, Hyderabad; Quickbird data: Pacific-Disaster centre

Figure 7. Visual interpretation of Tsunami affected area of (c) Vadakkupoyyur and (d) Velankanni villages using remote sensing data

Source: Pacific-Disaster centre

Figure 8. Impact of Tsunami on Agricultural and Horticultural lands in different villages of Nagapattinam and Kivalur Taluks Figure 9. Photographic views of Tsunami affected landforms and water bodies

Figure 9. Photographic views of Tsunami affected landforms and waterbodies

Table 2. Run-up level of seawater during Tsunami at selected locations along the coast of Nagapattinam and Kivalur taluks

Villages	Maximum run up level (m)	Distance of seawater inundation inland (m)	Nature of coastal land
Nagapattinam (Light house transect)	3.9	750	Coastal land with gentle slope interrupted by settlement
Vadakkupoyyur	6.1	2200	Low lying coastal land and presence of creeks like Vedaranyam canal
Therkupoyyur	4.6	250	Gentle beach followed by sand dunes of different elevations
Velankanni	4.3	950	Open beach and lands interrupted by settlement
Seruthur	5.6	1950	Low lying coastal land and presence of creeks like Velankanni canal
Pratabaramapuram	3.3	282	Coastal land protected by sand dunes and heavy plantations
Kilsethi	5.0	528	Coastal land with heavy plantation and presence of creeks

The run up levels and the prevalence of lower elevations within a distance of 2.0 km, where moderate to large settlements occur close to the coast, indicate the need to consider elevation based setback line in human settlement planning along the coastal areas of the villages. In fact, it is well known that Nagapattinam is one of the low lying coastal areas of the country and has experienced the fury of storm surges several times as it is known to be one of the possible landfall points for cyclones. The present run-up levels and inundation distances can be used as guidance to determine the safe locations for resettlement of affected population for the future (Ramanamurthy *et al.,* 2005). Similarly, the low lying areas adjoining the creeks (Vedaranayam and Velankanni canal) facilitated travel of Tsunami waves far inland, are too vulnerable as indicated by the landward penetration of seawater up to 2.2 km from the creek in Vadakkupoyyur village. So, adoption of elevation based setback lines or vulnerability lines are recommended for human settlement planning along the coastal villages of Vadakkupoyyur and Seruthur.

The large extents of croplands were also affected by seawater intrusion. Paddy, casuarina and mixed plantation (cashew + mango + coconut + other crops) adjacent to the seacoast were the most affected agricultural and horticultural crops. With the action of sea waves, the lands were physically damaged by removal of soil by erosion and deposition of large amounts of sand and other debris. The canal, irrigation and drainage channels were damaged. In addition, the seawater intrusion led to development of soil salinity, damaging the crop as well as making the agricultural lands unsuitable for cultivation. Salinity developed in soil due to accumulation of soluble salts. Salt deposition in Seruthur and Pratabaramapuram villages are clearly visible in the imagery. As seawater contains considerable quantities of sodium salts, its intrusion creates soil salinity.

4.2 Land use and Land cover change detection

Major changes to land use and land cover due to Tsunami were found along coastline of Nagapattinam district. The damage does not occur in a uniform manner, but is determined (among other factors) by the orientation of the coastline with respect to the direction of the Tsunami wave propagation as well as the topography of the land and the seabed in the coastal margins. Because of local variations, nearly 1320 ha was affected in Nagapattinam and Kivalur taluks, yet adjacent lands remained intact.

The harbor wave affected the agricultural and horticultural croplands by means of seawater intrusion. The invasion and receding action of harbor waves lead to the removal of soil by erosion and deposition of large amounts of sand, salt and other debris. The results on land use and land cover change detection studies revealed that the total of
747.91 ha of agricultural and horticultural croplands were affected by Tsunami, which includes paddy (610.52 ha), mixed plantation (67.04 ha) and casuarina (137.39 ha). Paddy fields were affected by erosion, salt deposition, water logging and other deposited sediment and the extent of area affected are 52.71 ha, 101.97 ha, 116.08 ha and 43.75 ha respectively. The widening of canals, tanks and newly formed brackish water channels occupied an area of 296.01 ha in paddy fields (Table 3) (Fig.10). The land use of mixed plantation (before Tsunami) was affected by soil erosion (8.76 ha), water logging (2.95 ha), salt deposition (19.24 ha) and other sediment deposition (34.85 ha). In case of casuarina fields soil erosion, water logging, salt and sediment deposition registered an area of 54.63 ha, 3.68 ha, 8.55 ha and 3.49 ha respectively.

The intrusion and receding action of the waves caused widening of canals in some parts of the study area. Deposition of sand particles in canal and water body occupied an area of 39.65 hectares. Tsunami has also caused land cover changes in sea, sand dune and saltpan areas. The receding action of waves led to deposition of eroded sand particles into the sea and thereby 11.27 ha of sea area were occupied by sand. Similarly, in some parts of the study area the intruded seawater did not recede back and it occupied an area of 2.86 ha. In Nagapattinam district, there are dense households from the coast up to 1.5 km. Tsunami has damaged the settlement area to an extent of 138.98 hectares. The study was carried out in Tsunami affected villages of Nagapattinam district to know about the impact on soil and water qualities. During January, February and March 2005, the Nagapattinam district received a rainfall of 6.6 mm, 326 mm and 120 mm, respectively. So, the effect of summer rainfall on soil and water qualities was also studied.

Table 3. Land use and Land cover changes in Tsunami affected areas of Nagapattinam and Kivalur taluks

Before Tsunami	After Tsunami	Area (ha)
Canal	Sand deposited	17.32
Casuarina	Eroded surface	54.63
	Salt Deposited	8.55
	Sediments deposited	3.40
	Waterlogging	3.68
Mixed Plantation	Salt deposited	19.24
	Sediments deposited	34.85
	Waterbody	1.24
	Waterlogging	2.95
	Eroded surface	8.76
Paddy	Eroded surface	52.71
	Salt deposited	101.97
	Waterlogging	116.08
	Waterbody	296.01
	Sediment deposited	43.75
Saltpan	Eroded surface	38.62
	Waterlogging	242.55
Sand dune	Sediment deposited	109.54
	Sea	2.86
Sea	Sand Deposited	11.27
Settlements	Eroded surface	40.58
	Partial damage of houses	47.59
	Waterlogging	4.14
	Sediments deposited	26.66
Waterbody	Sand deposited	22.33
	Total area	**1320.38**

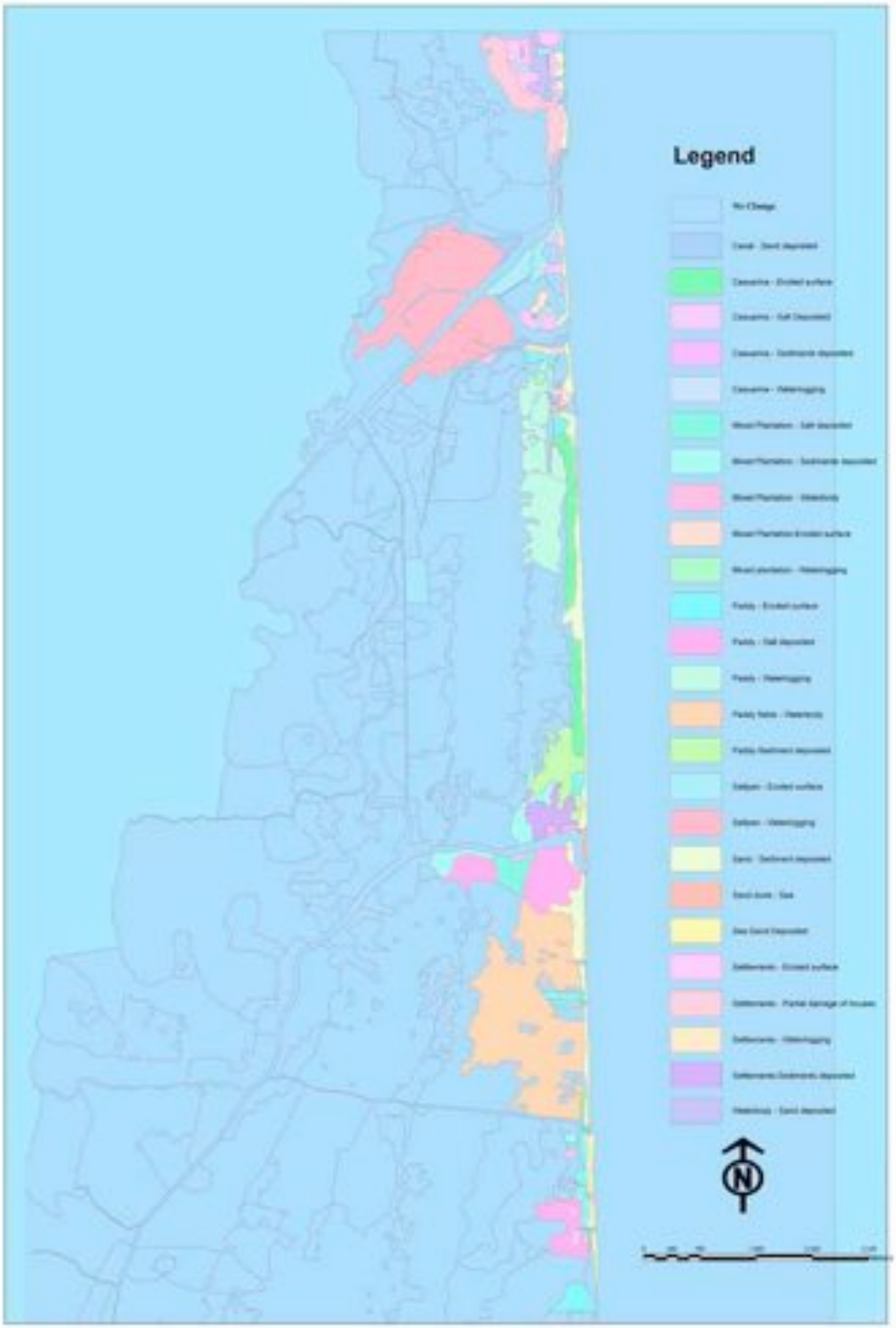


Figure 10. Effect of Tsunami on Landuse and landcover changes

4.3 Impact of Tsunami and effect of summer rainfall on Soil and Water qualities

4.3.1 Impact of Tsunami

In general, the results on soil qualities showed an increase in pH (0.34 – 2.64) and EC (0.00 – 3.86 dS m^{-1}) values in the Tsunami affected fields irrespective of distance from the sea and sampling depths. The pH and electrical conductivity values of soil samples received within 800 meters from the sea showed a varying trend and the values ranged from 7.35 – 8.64 and 0.03 – 3.94 dS m^{-1} respectively. However, the increase in soluble salt concentration and soil reaction does not occur in a uniform manner with the increase in distance from the sea, which showed the difference in the topography of the land and the barriers in the coastal margins. With the close view of the data, it was inferred that increase in pH values (1.67 – 2.64) was found to be higher in samples collected within 200 meters from the sea. Soluble salt concentration found to be higher in the samples collected between 500 and 600-meter distance from the sea and the values ranged from 3.84 – 3.86 dS m^{-1}. However the effect is marginal in irrespective of the sampling depth. The increase in soluble salt concentration with depth is evident within 300 meter and between 600 and 700-meter sampling distance from sea (Table 4).

The water reaction was found to be in alkaline range (> 8.00) in all the wells except one skimming well (SW 3) was in mildly alkaline range. Salinity levels are greater than permissible limit of 4 dS m^{-1} in all the wells except the ring well. Surface entry of seawater appears to be the primary cause for the salinity levels in the wells.

4.3.2 Effect of summer rainfall

The effect of summer rainfall on soil quality has benefited in leaching the soluble salts as a result of which, Electrical Conductivity has reduced in many locations. EC is harmless (below 1 dS m^{-1}) in most places (Table 5). A few fields registered high EC values (> 1 dS m^{-1}). These lands can be reclaimed with the receipt of another rain spell or by application of green manures or green leaf manures.

Table 4. Effect of Tsunami and summer rainfall on soil quality

Distance from sea	Depth (cm)	Before Tsunami		After Tsunami		Effect of Tsunami		After Summer Rainfall		Effect of Summer rainfall	
		pH	EC (dSm^{-1})	pH	EC (dSm^{-1})	pH	EC (dSm^{-1})	pH	EC (dSm^{-1})	pH	EC (dSm^{-1})
0-100	0-15	6.45	0.03	8.29	0.30	(+) 1.84	(+) 0.27	8.10	0.09	(-) 0.19	(-) 0.21
	15-30	6.56	0.03	8.64	0.52	(+) 2.08	(+) 0.49	8.10	0.15	(-) 0.54	(-) 0.37
100-200	0-15	5.78	0.01	8.42	0.32	(+) 2.64	(+) 0.31	6.26	0.06	(-) 2.16	(-) 0.26
	15-30	6.43	0.02	8.10	0.86	(+) 1.67	(+) 0.84	6.96	0.04	(-) 1.14	(-) 0.82
200-300	0-15	6.98	0.03	7.45	0.03	(+) 0.47	(+) 0.00	7.04	0.10	(-) 0.41	(+) 0.07
	15-30	7.01	0.01	7.35	0.05	(+) 0.34	(+) 0.04	7.04	0.10	(-) 0.31	(+) 0.05
300-400	0-15	7.08	0.04	8.38	0.62	(+) 1.30	(+) 0.58	7.59	0.07	(-) 0.79	(-) 0.55
	15-30	7.12	0.04	8.09	0.26	(+) 0.97	(+) 0.21	8.00	0.15	(-) 0.10	(-) 0.10
400-500	0-15	7.29	0.19	8.12	0.78	(+) 0.83	(+) 0.59	7.87	0.21	(-) 0.24	(-) 0.57
	15-30	7.43	0.08	8.27	0.54	(+) 0.84	(+) 0.47	8.03	0.36	(-) 0.24	(-) 0.19
500-600	0-15	6.77	0.08	7.75	3.94	(+) 0.98	(+) 3.86	7.66	1.84	(-) 0.09	(-) 2.10
	15-30	7.05	0.10	7.93	3.94	(+) 0.89	(+) 3.84	7.81	3.11	(-) 0.13	(-) 0.83
600-700	0-15	6.43	0.06	7.89	0.29	(+) 1.46	(+) 0.23	7.28	0.13	(-) 0.61	(-) 0.16
	15-30	6.73	0.06	7.54	0.48	(+) 0.80	(+) 0.42	7.35	0.24	(-) 0.19	(-) 0.24
700-800	0-15	6.91	0.09	7.96	0.84	(+) 1.06	(+) 0.75	7.58	0.18	(-) 0.38	(-) 0.66
	15-30	7.10	0.12	7.80	0.23	(+) 0.69	(+) 0.11	7.35	0.17	(-) 0.45	(-) 0.06

Table 5. Effect of Tsunami and Summer Rainfall on water quality

Well I.D.	Before Tsunami		After Tsunami		Effect of Tsunami		After summer rainfall		Effect of Summer rainfall		Remarks
	pH	EC ($dS\ m^{-1}$)	pH	EC ($dS\ m^{-1}$)	pH	EC ($dS\ m^{-1}$)	pH	EC ($dS\ m^{-1}$)	pH	EC ($dS\ m^{-1}$)	
SW1	7.59	0.89	8.30	4.11	(+) 0.71	(+) 3.22	7.79	1.03	(-) 0.51	(-) 3.08	Continuous pumping
SW2	6.94	0.83	8.04	7.30	(+) 1.10	(+) 6.47	7.89	5.85	(-) 0.15	(-) 1.45	No pumping
SW3	7.74	1.24	7.81	8.04	(+) 0.07	(+) 6.80	7.53	6.10	(-) 0.28	(-) 1.94	No pumping
RW	7.85	1.26	9.00	1.42	(+) 1.15	(+) 0.16	8.97	0.40	(-) 0.03	(-) 1.02	Continuous pumping
OP1	7.66	1.09	8.60	15.60	(+) 0.94	(+) 14.51	8.17	2.77	(-) 0.43	(-) 12.83	Continuous pumping
OP2	7.78	1.73	8.80	18.62	(+) 1.02	(+) 16.89	8.15	2.56	(-) 0.65	(-) 16.06	Continuous pumping

Note: SW – Skimming well; RW – Ring well and OP- Open pond

The effect of summer rainfall on water quality showed the dilution effect of soluble salts. Pumping of water has reduced the salinity levels in the well water samples and as well as in the open ponds. However, water from open ponds could not be used for irrigation till the EC falls below 3 dS m^{-1}. The well water samples showed an EC levels ranging from 1.94 to 3.08 dS m^{-1}. Even though there is a reduction in salinity level in these waters due to rainfall and continuous pumping, irrigation should be restricted to salt tolerant crops and varieties. Water reaction is within the normal range and only one ring well registered the pH values of 8.97, which may require application of gypsum.

5. TSUNAMI HAZARD MAPPING

Tsunami hazard maps are generated using a geographical information systems (GIS) approach for coastal Nagapattinam. Hazard maps are displayed as a continuous gradational color scale ranging from high hazard through medium, low to no hazard (Fig. 11). Hazard maps shows 20.6 per cent, 63.7 per cent and 15.2 per cent of the study area are coming under high hazard, medium hazard and low hazard category respectively (Table 6). The remaining percent shows no hazard to Tsunami.

Table 6. Tsunami hazard area (ha) in villages of Nagapattinam and Kivalur taluks

Hazard category	A	B	C	D	E	F	G	H
High hazard zone	335.28	42.43	40.11	55.95	43.75	229.17	119.88	93.37
Medium hazard zone	472.51	23.24	18.19	288.23	199.98	913.97	600.67	458.8
Low hazard zone	195.11	4.83	-	159.36	38.68	40.92	72.51	200.85
No hazard	20.96	1.34	0.65	-	-	-	-	-
Total area (ha)	1023.86	71.84	58.95	503.54	282.41	1184.06	793.06	753.02

A: Vadakku Poyyur; B: Karuvelankadai; C: Papakoil; D: Therkupoyyur; E: Velankanni;
F: Pratabaramapuram; G: Tirupoondi Kilsethi; H: Viulundamavadi

In this study, the main focus was to generate hazard mapping to quantify the extent of the area prone to Tsunami. The criteria taken into consideration for assessment of hazard mapping were types of land adjoining the coast and the topographical difference pertaining to the land. These maps are GIS based to facilitate ready adaptation

Figure 11. Tsunami Hazard Map generated using GIS approach

by planners and emergency managers. The maps are intended for educational purposes, to improve awareness of Tsunami hazards and to encourage emergency planning efforts of local and regional organizations by illustrating the range of possible Tsunami events. Criteria boundaries defined by Patton and Dengler (2004) were adopted to delineate the regions and it has to be refined by comparing with the Tsunami events. Factors like Tsunami strength and its character were not considered in the hazard mapping.

6. CONCLUSIONS

A total of seven revenue villages in the coastal taluks of Nagapattinam and Kivalur were affected due to Tsunami 2004. Prevalence of lower elevations in the study area has led to the landward penetration of seawater up to 2.2 kilometers. The study on land use and land cover changes due to Tsunami revealed that a total of 747.91 ha of agricultural and horticultural crop lands were affected, which includes paddy (610.52 ha), mixed plantation (67.04 ha) and casuarina (137.39 ha). The lands were affected by soil erosion, salt deposition, water logging and other deposited sediments and debris. Tsunami affected fields showed an increase in pH and EC values, irrespective of distance from the sea. The water reaction was found to be in alkaline range (> 8.00) in most of the wells. Salinity levels are greater than 4 dS m^{-1} in all the wells except the ring well. The effect of summer rainfall on soil and water quality showed the dilution of soluble salts. Pumping of water has reduced the salinity levels in the well water samples and as well as in the open ponds.

Tsunami hazard maps generated using GIS approach depicts the relative Tsunami hazard of coastal Nagapattinam. The criteria taken into consideration for assessment of hazard mapping were types of land adjoining the coast and the topographical difference pertaining to the land. Hazard maps showed 20.6 per cent, 63.7 per cent and 15.2 per cent of the study area fall under high hazard, medium hazard and low hazard category respectively. Criteria boundaries adopted to delineate the regions have to be refined by comparing with the existing Tsunami events. Further, the factors like Tsunami strength and its character has to be considered in the hazard mapping.

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BENTHIC FORAMINIFERAL AND ITS ENVIRONMENTAL DEGRADATION STUDIES BETWEEN THE TSUNAMIGENIC SEDIMENTS OF MANDAPAM AND TUTICORIN, SOUTH EAST COAST OF INDIA

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ABSTRACT

The Gulf of Mannar is a transitional zone between the Arabian Sea and Indian Ocean proper and is connected with the Bay of Bengal through a shallow sill, the Palk Strait. The study area extends from Mandapam to Tuticorin on the southern coast of Tamil Nadu (India) over a distance of 120 km. It is bound in the northeast by Rameshwaram Island, in the east by the Bay of Bengal, in the west by the Eastern and Western Ghats, and in the south by Tuticorin. A total of 36 sediment samples were collected from the beach (6) and the offshore (30) area in the study region. The offshore samples were collected at six transects keeping the stations at Mandapam (5 nos), Valinokkam (5 nos), Vaippar (5 nos), Vembar (5 nos), Kallar, (5 nos) and Tuticorin (5 nos). Totally, 77 benthic foraminiferal species (Post-tsunami) and varieties belonging to 39 genera, 13 families, 10 superfamilies and 4 suborders have been reported and illustrated. The following species are widely distributed in the pre and post-tsunami samples namely S*piroloculina communis, Quinqueloculina elongatum, Q.lamarckiana, Q. seminulum, Triloculina trigonula, Cibicides lobatululs, Ammonia beccarii, A. dentata, A.tepida, Elphidium crispum* and *Assilina ammonoides*. Grain size studies shows the frequency curves vary from unimodal to bimodal in places of river discharge from the Vembar, Kallar, Vaippar and Tamiraparani, as a result of which an additional sub-population is deposited. At Mandapam and Tuticorin, the total species are increasing in the deeper depths whereas in Kallar there will be reverse trend which decreases with depth. Similarly, the living species also have the same trend at Vallinokkam. The scatter plot of salinity versus living species shows a positive correlation. The scatter plot of organic matter versus living species shows strong negative correlation and positive correlation with dead species showing a negative relation with the biomass. Further, the trend of organic matter vs. carbonate indicates that the littoral drift of sediments brought foraminifera from the inner shelf regions and has played a great role in the contribution of dead species, as well as microfossils. The present study indicated that the sediments were brought from the inner shelf.

1. INTRODUCTION

Micropaleontology is a discipline well suited to the study of environments, environmental changes, and environmental monitoring of present day contaminated and polluted areas. Of which, foraminifers, almost exclusively marine, unicellular protists, generally consisting of a hard covering of calcium carbonate called a test, have extensively been used for studies related to paleoclimatic reconstruction, sediment transport, archaeology, etc.

After the 26th December 2004 earthquake, a major tsunami wave train traveled with tremendous velocity and transported large quantities of water and sediments, including microfossils. The present study used environmental characteristics and foraminifera distribution to determine the impact of tsunami sediments. The Gulf of Mannar receives input through a number of rivers and streams, of which the Tamiraparani followed by Vaipar River, are the major sources. The coastal area between Mandapam and Tuticorin that was studied was affected by recent tsunamis. The outcome of the tsunami sediment studies of this area based on micro fauna, particularly foraminifera, will give a clear picture about the impacts of tsunami and environmental degradation in this region.

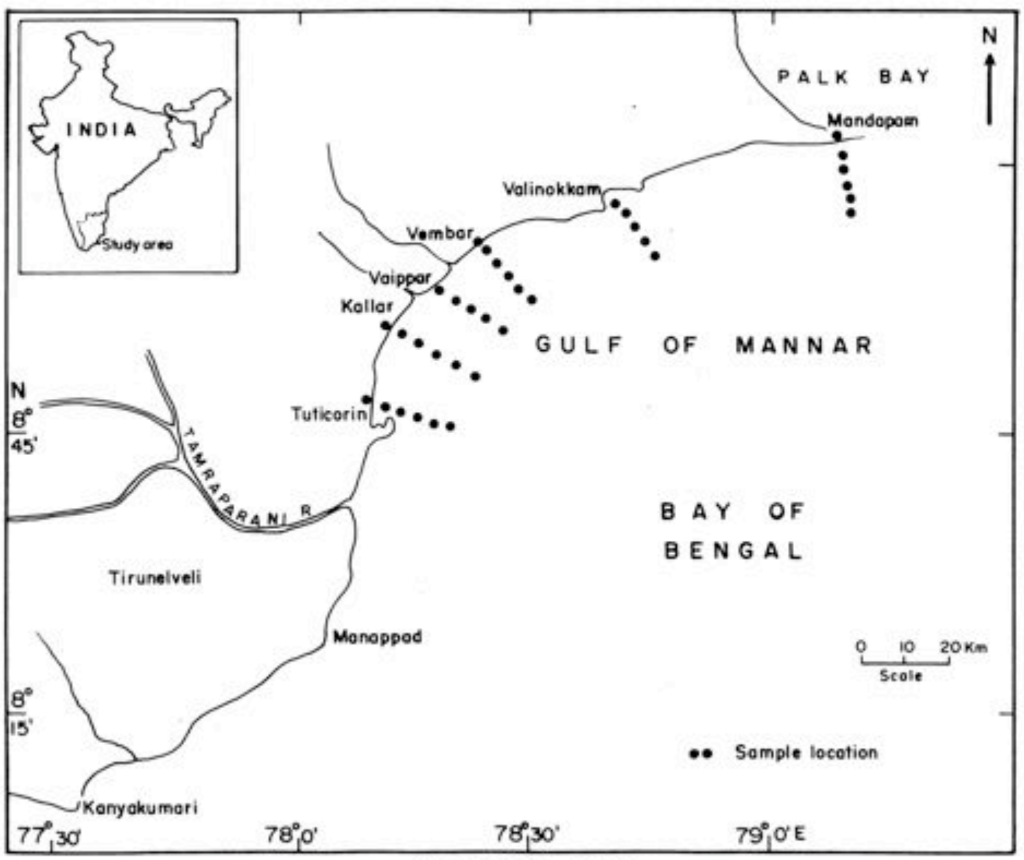

Fig.1 LOCATION MAP

Mandapam South – Pamban bridge **Marine terrace at south of Mandapam**

Marine calcareous sand stone at Valinokkam **Sand dunes at Kallar region**

Shurbs at Vaippar beach **Beach ridge at Vembar beach**

Fig. 2 Coastal landforms of the study region

2. STUDY AREA

The present study area is along the southern coastal tract of Tamilnadu. The coastal stretch between Mandapam and Tuticorin, in the southeastern part of the Tamilnadu State in India, extends over a distance of about 150 km in length. This area is located between 8º 45' to 9º 15' N 78º 35' to 79º 15' E covering the districts of Ramanathapuram and Tuticorin (Fig.1). The study area is situated on the northeastern side near Rameswaram Island, in the east of the Bay of Bengal, bounded in the south by the port of Tuticorin. The study area includes marine terraces, sand dunes, beach ridges, estuaries, floodplains, beaches, mangroves, peneplains, uplands, sea cliff, etc. (Fig.2). The coastal stretch of Tuticorin was extensively studied due to the presence of a major port. Between Tuticorin and Sippikulam, the beach is flat and narrow. The islands of Pandyan Tivu, Van Tivu, Kasuvari Tivu, Vilangu Shuli Tivu and Kariya Shuli Tivu are present within 5 km of the coastline along this segment and offer protection from wave action and erosion.

Three types of beaches are observed in the study area. They are rocky beaches, pocket beaches and sandy beaches. Rocky beaches exist at the Valinokkam and Terukkumukkaiyur coastal region, whereas sandy beaches can be found along Valinokkan, Bay, Keelmundal, Kannirajapuram, Vembar, Vaippar and the Tuticorin coastal areas. A pocket beach was observed near Narippaiyur. The beaches are normally gentle in slope and their width ranges from about 20 to 70 meters. In the Valinokkam, Vaippar and Tuticorin coastal region a well-defined beach ridge system has been recognized that is discontinuous and varies in length and width. The beach ridges are distributed a few kilometers away from the Tuticorin coastline. Spit formation was identified in Valinokkam and Tuticorin. The formation and distribution of spits suggest seaward progradation of the coast in the study area. The drainage pattern of the area is mainly controlled and influenced by the presence of perennial rivers like Gundar, Vembar, Vaippar and Kallar.

3. MATERIALS AND METHODS

Before sample collection, a base map in the scale 1: 50,000 was prepared using the toposheets (NO. 58L/13, 58L/1 and 58M/16). The fieldwork was done during the month of March 2006. Using a private motor launch, a unit volume of 100 ml of wet sediment sample taken from the top 1 cm of the substratum was preserved immediately in 10% neutralized formaldehyde. A total of 36 sediment samples were collected from beach (6) and Offshore (30) in the study region. The offshore samples were collected at six transects keeping the stations at Mandapam (5 nos), Valinokkam (5 no), Vaippar (5 nos), Vembar (5 nos), Kallar, (5 nos) and Tuticorin (5 nos). In the same locations, samples have already been collected by earlier workers (S.M.Hussain – Tuticorin region and Suresh Gandhi, Mandapam region, Rajesakhar – Manappad Region)) has been utilised for comparisons studies.

Global Positioning System (GPS) was used to locate the sample sites in the offshore region. At each station, bottom water samples were also collected and were preserved by adding 10 ml of chloroform. Temperature, pH and Eh were measured in the field immediately after the collection of each sample. In the present study, following Walton's (1952) technique, the sediment samples preserved in neutralized formalin were subjected to laboratory treatment. The preserved samples were washed over an ASTM 230 mesh sieve (0.063 mm) to remove the silt and clay. The sieve with the residue was kept for about an hour in a tray containing an aqueous solution of rose Bengal (1 g of rose Bengal dye in 1 liter of distilled water) ensuring that the residue on the sieve mesh was fully covered by the solution. Then, the material on the sieve was washed to remove the excess stain and dried. The foraminiferal tests were then separated from the residue by floatation method using carbon tetrachloride (Cushman, 1959). As a check, the residue after floatation was re-examined under a binocular stereo-microscope for the presence of any foraminiferal tests left unconcentrated. They were handpicked using `00' Windsor Newton sable hairbrush.

4. RESULTS AND DISCUSSION

4.1 Grain Size

In the present study 24 samples from 6 beach stations have been analyzed. Table. 1 shows the various textural parameters for beach samples (24) obtained through graphic and moment methods. In order to facilitate interpretation of statistical data in the study area, the different sub-population has been identified. In the Valinokkam zone, the frequency pattern point towards the presence of polymodal distribution having peaks at 1.5 φ, 2.25 φ and 2.75 φ. The coarser population of sediments is indicative of the influence of open sea conditions and strong winnowing action that in turn results in the removal of fines. It is supplemented by the presence of rocky beaches around the region. In the Vaippar zone of the study area, the frequency curves have peaks at 2.25 φ, 2.75 φ and 3.75 φ. The characteristic presence of two populations may be attributable to the role of multi sources, probably the contribution of oceanic as well as the rivers like Vembar, Vaippar and Kallar of the study area. Despite the prevalence of high-energy conditions here, the continuous presence of fine sediments may be ascribed to the prolific supply through the rivers as well as from the shelf. The Tuticorin zone also indicates a polymodal distribution. The dominance of coarse size grade in the total population indicates the high-energy conditions that result in the removal of fines. The presence of rocky beaches and convergence of wave pattern near Tamirabarani river mouth accentuate the coarsening of sediments.

The mean reflects the overall average grain size of the sediment as influenced by source of supply and environment of deposition. In the Mandapam zone mean values ranging form 1.48 φ to 1.84-φ indicating with medium sand. In the Valinokkam zone, mean value ranges from 1.46 φ to 1.95 φ indicating a prominent distribution of medium sand in the study area. The mean values demonstrate a gradational increase in the Terkumukkaiyur region of the zone. In the Vaippar zone, mean value fluctuates from 1.28 φ to 2.6 φ and it's characterized by medium sand and fine sand. The lack of winnowing action due to the protected nature of bay leads to the accumulation of the fine sediments. The mean values of Tuticorin zone ranges form 1.35 φ to 1.95 φ indicate the presence of medium sand. It indicates the northerly movement of Tamirabarani riverine sediments by littoral currents. In addition to this, the high-energy environments can also alter the nature of the sediments.

4.1.1 Standard Deviation

The Mandapam and Vallinokkam zones shows more or less similar sorting. The Valinokkam zone sorting value ranges from 0.32 φ to 0.69 φ indicates very well sorted to moderately well sorted nature. The sorting value in Vaippar and Kallar zone ranges from 0.25 φ to 0.80 φ. It indicates a very well sorted to moderately sorted nature. In the Tuticorin zone, sorting value varies from 0.34 φ to 0.62 φ. It indicates a very well sorted to moderately well sorted nature. In the Vaippar zone, the very well to moderately sorting nature may be due to the addition of sediments of different grain size from the reworking of beach ridges or by fluvial action and the prevalence of strong wave convergence throughout the year.

4.1.2 Skewness

The range of skewness values of Mandapam to Vembar, Vembar to Kallar and Kallar to Tuticorin are -0.39 to 0.95, -0.78 to 0.77 and -0.27 to 0.74, respectively. In general, based on the classification of Folk and Ward (1957) the skewness values of these beach sands vary from very negatively skewed to very positively skewed.

In the study region, the sediment skewness varies from near symmetrical to positively skewed. This is probably due to the presence of numerous coastal creeks In the Valinokkam zone, the sediments show coarse skewed to fine skewed (-0.39 to 0.95). It implies the prevalence of high and low energy environments in different wave directions, entailing a mixed distribution of coarse and fine sediments. In the Vaippar zone the sediments show a near symmetrical to negatively skewed nature, suggesting a high-energy environment. Due to washing and backwashing of waves, coarser sediments are retained and get entrapped amidst finer sediments. In the Tuticorin zone, the sediments show very negatively to very positively skewed nature indicative of the prevalence of mixed energy environment.

4.1.3 Kurtosis

The graphic kurtosis varies from 0.51 to 1.26 in the Valinokkam zone. In other words, the Valinokkam zone is very platykurtic to leptokurtic, whereas the Vaippar zone is very platykurtic to very leptokurtic and the Tuticorin zone is very platykurtic to very leptokurtic. The leptokurtic to platykurtic nature indicates multiple environment i.e., one derived from riverine/aeolian environment and the other primarily derived from marine environment. The moment kurtosis values are found to vary from 1.83 to 3.69, 1.65 to 5.46, and 1.60 to 3.68 in the Valinokkam, Vaippar and Tuticorin zones of the study area, respectively. In the Vaippar zone, a strong variation in the Kurtosis value reflects relict sediments along the beach.

4.2 Distribution and Ecology of Foraminifera

The widely utilized classification proposed by Loeblich and Tappan (1987) has been followed in the present study. A total of 77 benthic foraminiferal species (Post-tsunami) and varieties belonging to 39 genera, 13 families, 10 superfamilies and 4 suborders have been reported and illustrated. All the illustrated specimens have been deposited in the Department of Geology, University of Madras, Guindy Campus, Chennai – 600 025. The present study includes the results of the distribution of foraminiferal assemblages in the study area. The *Milionina* and *Rotalina* occupy the dominant place in the post tsunami samples of the study area.

4.2.1 Beach

Forty-nine species are identified from the analysis of 6 beach samples. Among them the species, *A.beccarri* shows a higher abundance in all the stations, barring one or two, followed by *A.dentata* and by *Q.seminulum* and *Elphidium crispum* in all the stations. In general, the beach sample shows that pre-tsunami species are lesser in amount compared to the post-tsunami species. In the study area due to tsunami, the distributions of species are slightly higher in number on the beaches.

4.2.2 Offshore

Out of the 76 taxa identified, only 18 represent the living crop at the time of post-tsunami sample collection. Among them, most of the species are sparingly distributed. The actual number and distribution of total and living foraminiferal species in the offshore region is shown in the Table.2. The significant variation in the distribution of total and living species assemblages may be due to sedimentation as well as due to the wave actions and tidal currents (Murray, 1973). Since the samples are collected after the tsunami, due to the wave actions, the living dead populations also varied in this region.

The general trend in modern shallow water foraminiferal assemblages is the increasing species diversity with increasing salinity gradients and environmental stability. The genus *Ammonia, Elphidium, Pararotalia, Quinqueloculina, Triloculina* and *Spiroloculina* are dominates the total assemblages in the study region. The following species are widely distributed in the pre and post-tsunami samples namely *Spiroloculina communis, Quinqueloculina elongatum, Q.lamarckiana, Q. seminulum, Triloculina trigonula, Cibicides lobatululs, Ammonia beccarii, A.dentata, A.tepida, Elphidium crispum* and *Assilina ammonoides*. The following species are found in lesser amount in all the stations, namely, *Elphidium discoidale, Rectobolivina raphanaus, Cribrononion simplex, Cymbaloporetta bradi, Eponoides rapandus, Spiroloculina aqua* and *S. inca.* Specimens of all species are abundant in the deeper depths.

4.3. Offshore – Pre- and Post- Tsunami

At Mandapam and Tuticorin, the total species increases in the deeper depths whereas in Kallar there is a reverse trend that decreased in deeper depths. The assemblage living species display the same trend at Vallinokkam.

The genus *Ammonia, Elphidium, Quinqueloculina, Triloculina* and *Spiroloculina* dominates the total assemblages followed by *Amphistegina, Globigerina* in the study region. The following species are widely distributed in the post-tsunami samples namely S*piroloculina communis, Quinqueloculina elongatum, Q.lamarckiana, Q. seminulum, Triloculina trigonula,* *Cibicides lobatululs, Ammonia beccarii, A. dentata, A.tepida, Elphidium crispum* and *Assilina ammonoides.*

4.3.1 Station-wise distribution of total and individual foraminiferal species

The distribution of total foraminiferal species according to the different stations shows an appreciable variation among the stations. At Mandapam and Tuticorin, an increasing trend in the total number of species is noticed in the deeper depths. The stations, Kallar and Vallinokkam show the similar trend but increasing trend is noticed from shallow to deeper depths, followed by a sudden decrease. The individual species distribution shows that diversity is greatest towards the shallow regions than the deeper. Even though, the individual species are more abundant in the shallow regions the total number of foraminiferal species are more abundant in the deeper regions with depths ranging form 8 to 12 m.

4.3.2 Station-wise total diversity of Living species

Total number of living foraminiferal species in the offshore region shows (fig.4) that an increase in the number of living foraminifera is observed in post-tsunami samples at the Tuticorin region at deeper depths than the other regions. The lowest diversity is noticed in the shallower depths at Vallinokkam and Kallar region and more or less a close similarity in the trend is noticed. Disturbance in the seabed resulted in low living diversity. Wherever the total species is high, the number of living species is increasing.

4.4. Ecology of the Foraminifera

The salinity measured during the present studies varies from 30.16 ‰ to 31.07 ‰. In all the stations, the salinity shows little variation due to mixing of water within the bay. Furthermore, the river mouth areas like Vaippar, Kallar, and Vembar, etc. display similar salinity. The scatter plot of salinity vs. living species shows a positive correlation (Fig. 3). At Tuticorin salinity values increased towards the deeper depths as did the number of living species. The correlation between depth vs. living species is positive. In the study region, the beach sands are coarser. In the offshore region, the sand is dominant over silt in most stations. Silty sand predominates in the deeper portion. Living foraminiferal populations are more abundant in the silt and silty sand region of the study area. At Vembar silt and silty sand are dominant.

4.4.1 Organic matter

In the study area, organic content ranges from 1.232% to 0.123% are noticed. In the near shore region the organic matter does not shows any variation. The scatter plot of organic matter of living species shows strong negative correlation (Fig.3) and positive correlation with dead species (Fig.3) shows a negative relation with the biomass. Further, the trend of organic matter vs. carbonate (Fig.3) suggests littoral drift of sediment brought from the inner shelf regions have played a significant role in the contribution of dead species as well as carbonate shells. The rise in total amount of living species in deeper portion at Tuticorin may be due to oxygenated conditions in that region

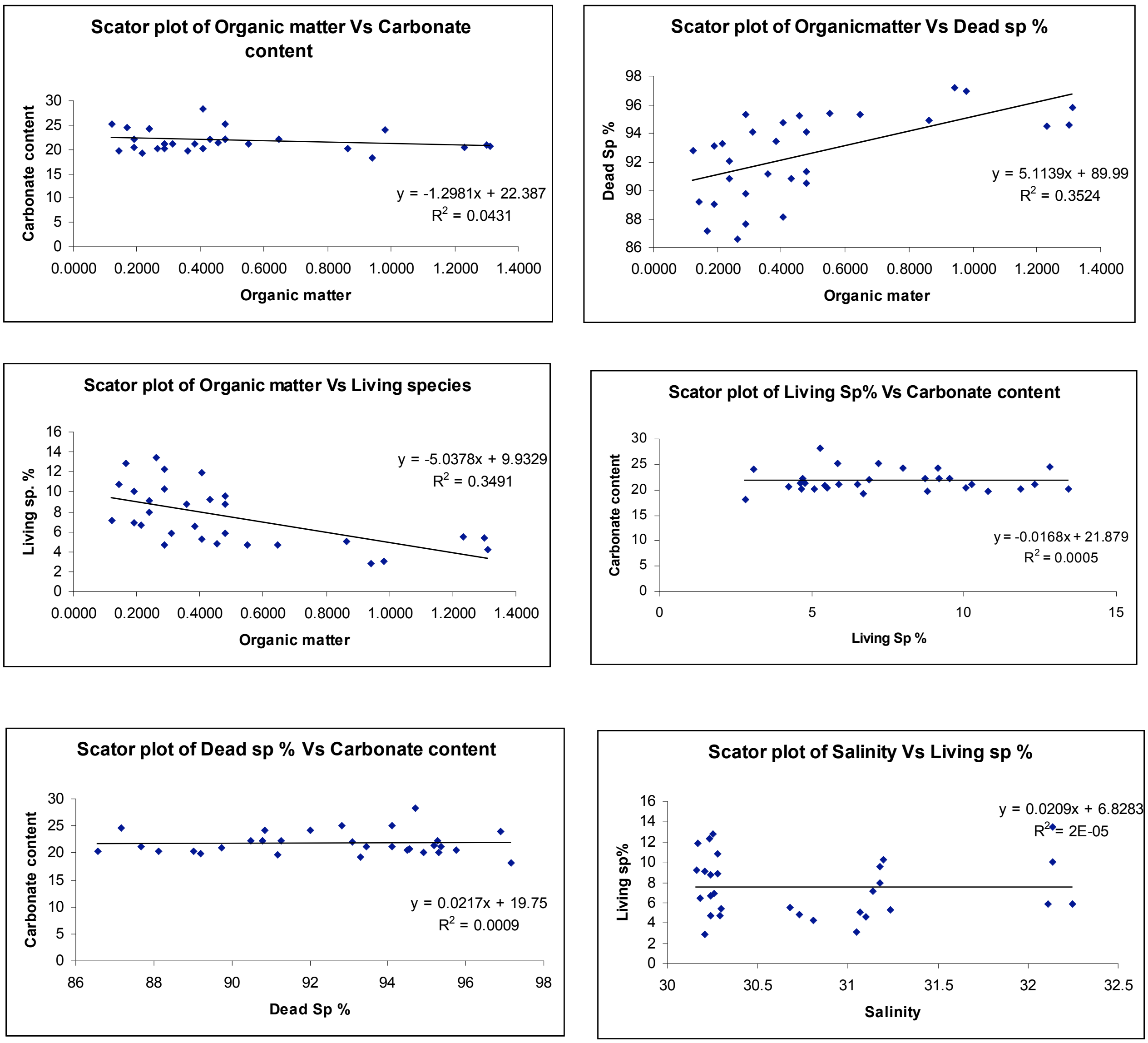

Fig.3. Scatter plots for the different environmental parameters

4.4.2 Calcium Carbonate

In the study area higher carbonate content in the shallow depths in all the stations is observed. In Kallar it is decreased in the deeper depths. The scatter plot of carbonate content vs. living species and organic matter shows the negative correlation (Fig.3) and positive correlations with dead species (Fig.3). It means that weak and strong relation is being maintained between carbonate and living dead species. But, now carbonates must have been the product originated from the other factors, probably the drifted shells from elsewhere or from the coral reef region in the in situ. It indicates that the carbonate present in this region is *in situ*.

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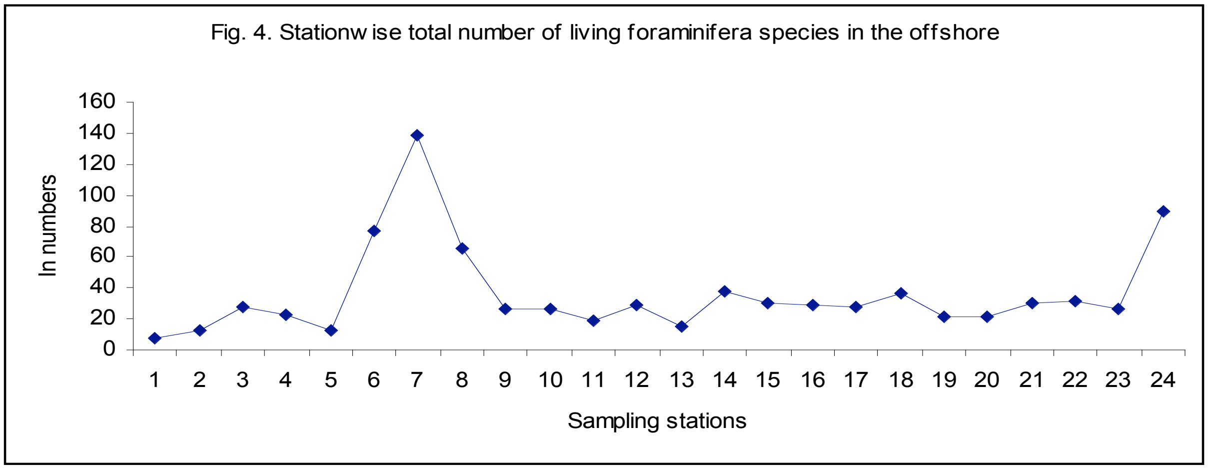

Fig.4. Station-wise total diversity of Living species

4.4.3 Morphological Deformities

In the present study, morphological abnormalities were observed in the species *Osangularia* and *Pararotalia* having abnormal and overgrowth apertures. The broken specimens were found in the beach, offshore and inland region. It may be due to the tidal actions, and strong current activity and industrial wastes at thermal power stations, and harbor, Tuticorin.

4.5. Comparisons with Pre-Tsunami

The comparison of post-tsunami and pre-tsunami data is possible due to earlier workers like S.M.Hussain and Rajesekhar and Suresh Gandhi (2000). The study reveals that in the offshore region at the shallow depths, the fossil enrichment is more in post tsunami sediments than the pre-tsunami samples. Due to the tsunami activities, large amount of sediment were transported from the deeper depths and deposited near the shore regions, hence higher species diversity is noticed near shore region. Table.3. shows the checklist of pre-tsunami and post-tsunami fossils.

The fieldwork carried out in the coastal belt, indicates that the topography has been smoothened as the tsunami overtopped the dune, ridges and transported the material into the low lying areas. It is difficult to estimate where the material is transported unless the dune material is lithologically different from the soil inland. Sand deposits over mudflats, and alluvial flats clearly reveal that a considerable amount of beach deposit have been transported inland. While the eroded features provide insight into the transport of the sediments, how much material has been brought from the deep sea and continental shelf is not clear. Clasts of clay and rare coral debris indicate that the tsunami brought sediments from the sea.

A considerable amount of sediments are transported into the sea via carved channels as much as 5 m wide and 30 m long during the tsunami drain back. So, it is evident that transportation from sea to land, transport of beach material to inland and transport back to the sea have taken place. The erosion appears to be more in the northern part of the area investigated; on the other hand deposition dominates over erosion in the southern part of the area, which is characterized by flat topography (Sanjay Gandhi, 2005).

The total distribution of foraminifera is higher at Mandapam and Tuticorin sector, than in Kallar and Vallinokam. The configuration of the beach may control the distribution of foraminifera species from offshore to the beach. The arcuate nature of the bay and wave energy conditions is the major controlling factors for the distribution of foraminifera.

The study area receives inputs from many small channels and rivers like Vembar, Vaippar, Kallar and Tamirabarani. The land areas through which these rivers and channels flow are well known for agricultural activities. Tsunami sediments entered through the rivers and were deposited inland. The total populations of foraminiferal species are very low in the beach region probably due to erosion. Living populations are also found to be low to moderate in number in the study area.

Several authors, (Yassini and Jones, 1995; Murray, 1991; Nigam et al., 1979; Haig, 1988) have studied and reported the distribution of foraminifera in various regions and concluded the distribution of species reflect different environments. Kamalakanan et al (2005) have studied the tsunami sediment from the Nagapattinam coast and inferred that the majority of foraminiferal species are inhabit coastal water and hence the sediment would have been removed from the near shore coastal water zone by tsunami waves and spread over the coastal line. Rao et al., (2005) have studied the tsunami laid sediments along the North Chennai coast and suggested that the fossils distributed in these areas have been transported from the inner shelf region, probably at depths less than 30 m. From the overall studies of foraminiferal distribution in this region, it may be inferred that the species distribution in the offshore region is mainly derived from the inner shelf region. Due to tsunami activities the offshore species are deposited in the beach, accompanied by transport of beach material to inland and transport back to the sea.

5. CONCLUSIONS

The study of a composite cosmopolitan fauna of 76 species belonging to 39 genera, 24 families, 16 super families and 5 suborders from the samples collected from post-tsunami beaches and offshore samples is reported here. Grain size studies shows the frequency curves vary from unimodal to bimodal in the proximity of river discharge from the Vembar, Kallar, Vaippar and Tamiraparani. The offshore region of Mandapam and Tuticorin receives higher species diversity than the Kallar in post tsunami samples. In general, the distribution of pre-tsunami fossils is less than the post-tsunami distribution. This may be due to the impact of tsunami action. Furthermore, salinity and carbonate content are the controlling factors for the distribution of foraminifera in this region. A thorough review of literature of foraminiferal research from the Indian subcontinent reveals that the foraminiferal species distributed in this region were brought from the deeper depths particularly form the inner shelf region due to tsunamigenic activities. It will be essential to track the source of sediment in the deeper part by carrying out a detailed investigation on the microfossil studies.

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Table.1 RESUTLS OF GRAIN SIZE ANALYSIS FOR BEACH SAMPLES

Stations	s.no	ME-Q	MSD-Q	MCD-Q	MSK	MKU	MED-Q	M-Q	SD-Q	SK	KU	FP-Q
		Moment methods						Graphic method				
MANDAPAM												
BERM	1	1.83	0.48	-0.33	-0.03	1.2	1.87	1.86	0.45	0.48	0.48	-0.99
HIGHTIDE	2	1.84	0.43	1.66	0.17	1.14	1.8	1.8	0.4	0.49	0.44	-0.98
MIDTIDE	3	125	0.29	-0.38	0.03	1.12	1.49	1.8	0.28	0.12	0.54	0.98
LOWTIDE	4	1.45	0.26	2.75	0.84	1.74	1.48	1.4	0.25	0.15	0.82	0.97
VALINOKKAM												
BERM	5	1.87	0.45	-0.33	-0.03	1.1	1.83	1.81	0.42	0.44	0.45	-0.98
HIGHTIDE	6	1.84	0.43	1.66	0.17	1.14	1.8	1.8	0.4	0.49	0.44	-0.98
MIDTIDE	7	1.45	0.28	-0.34	-0.03	1.08	1.43	1.4	0.269	0.19	0.44	0.99
LOWTIDE	8	1.44	0.24	2.71	0.85	1.7	1.42	1.41	0.22	0.13	0.79	0.95
VEMBAR												
BERM	9	2.11	0.54	0.48	0.9	1.13	2.1	2.08	0.59	0.15	0.79	0.96
HIGHTIDE	10	2.06	0.59	-0.94	-0.14	1.4	2.04	2.03	0.65	0.27	0.5	-0.98
MIDTIDE	11	2	0.57	0.48	0.71	2.39	2	1.98	0.55	0.24	1.41	1.02
LOWTIDE	12	1.94	0.32	0.64	0.06	1.12	1.93	1.91	0.32	0.3	0.45	-0.98
VAIPAR												
BERM	13	2.1	0.78	-0.67	-0.16	1.16	2.08	2.05	0.74	-0.37	0.42	0.99
HIGHTIDE	14	2.05	0.74	0.73	0.1	1.25	2.04	2.01	0.72	0.3	0.46	1.03
MIDTIDE	15	2.02	0.69	0.2	0.02	1.18	2.01	1.99	0.69	0.27	0.46	-0.98
LOWTIDE	16	1.92	0.51	-0.42	-0.28	1.26	1.92	1.9	0.5	-0.92	0.49	-0.98
KALAR												
BERM	17	2.01	0.62	0.61	0.77	1.88	2	1.99	0.6	0.76	0.62	0.99
HIGHTIDE	18	1.57	0.43	0.67	0.61	2.36	1.57	1.5	0.43	0.21	0.75	0.24
MIDTIDE	19	1.69	0.39	0.23	0.71	2.24	1.63	1.61	0.33	0.33	1.19	-0.98
LOWTIDE	20	1.58	0.27	0.59	0.71	1.88	1.56	1.53	0.22	0.61	0.45	0.99
TUTICORIN												
BERM	21	1.67	0.58	0.85	0.23	2.11	1.66	1.64	0.53	0.94	0.8	0.96
HIGHTIDE	22	1.69	0.53	0.11	0.39	2.32	1.69	1.63	0.5	0.65	0.71	0.96
MIDTIDE	23	1.64	0.34	0.25	0.02	2.81	1.64	1.62	0.34	0.84	0.79	0.96
LOWTIDE	24	1.62	0.31	0.92	0.38	2.21	1.62	1.6	0.3	0.45	0.73	0.96

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Table.2. Distribution of total and living foraminiferal species between Mandapam and Tuticorin (offshore)

Sl.No	Station Numbers	Mandapam										Valinokkam									
	Depth in mts	1m		2m		4m		5m		5.5m		2m		3m		4 m		4.5m		5m	
	Name of Species	L	T	L	T	L	T	L	T	L	T	L	T	L	T	L	T	L	T	L	T
1	*Ammobaculites exiguus*					0	2	0	1	0	3	0	1								
2	*Textularia agglutinans*			0	1			0	2					0	1	0	2				
3	*Textularia conica*											0	1								
4	*Vertebralina striata*			0	2	0	1	0	2	0	3	0	2	0	1	0	4	1	4	1	3
5	*Edentostomina cultrata*	0	1	0	2													0	1	0	1
6	*Adelosina laevigata*	0	2	0	7	0		0	8	0	12										
7	*Spiroloculina angusta*			0	2	0	1														
8	*Spiroloculina affixa*	0	1	0																	
9	*Spiroloculina communis*	0	4	0	3	0	1	1	14	1	10					0	2	0	1	0	2
10	*Spiroloculina costifera*					0	1	0	1												
11	*Spiroloculina depressa*	0	1	0	2	0	1	0	2	0	1										
12	*Spiroloculina orbis*					0	2	0	1	0	1			0	1						
13	*Spiroloculina sp1*	0	1									0	1								
14	*Spiroloculina sp2*	0	1																		
15	*Massilina secans tropicalis*					0	2	0	2	0	1										
16	*Vertebralina striata*					0	1	0	1							0	2	0	1		
17	*Quinqueloculina agglutinans*			0	2	0	4	1	12	0	7										
18	*Quinqueloculina bicostata*	0	2	1	5	0	1		8	0	2										
19	*Quinqueloculina costata*	0	1	0	3			0	3												
20	*Quinqueloculina elegans*			0	2	0	1	0	5	0	1										
21	*Quinqueloculina lamarckiana*	0	2	1	5	2	12	1	7	0	5	0	2	0	2	0	3	0	2	0	1
22	*Quinqueloculina polygona*	0	3	0	2	0	4	0	8	0	7										
23	*Quinqueloculina seminulum*	0	12	2	12	1	8	0	12	0	5	0	2	0	4	0	4	0	6	0	1
24	*Quinqueloculina elongatum*			0	3	0	2	0	1			0	4	0	1	0	1				
25	*Quinqueloculina tropicalis*			0	8	0	6	0	3			0	3								
26	*Quinqueloculina sp 1*																				
27	*Quinqueloculina sp 2*																				
28	*Miliolinella circularis*			0	2	0	2	0	1			0	1	0	1						
29	*Triloculina oblonga*																				
30	*Triloculina insignis*	0	2	0	2									0	2	0	1				
31	*Triloculina schreiberiana*	0	1	0	5																
32	*Triloculina terquemiana*	0	1	0	2																
33	*Triloculina tricarinata*	0	8	1	18	0	16	0	3			0	2								
34	*Triloculina trigonula*	0	2	0	18	1	23	2	32	1	29	0	3	0	4	0	4	0	2	0	1
35	*Hauerina bradyi*					0	1	0	0	0	1										
36	*Articulina pacifica*	0	2	0	1																
37	*Rupertianella rupertiana*	0	1	0	3	0	4	0	4	0	1			0	2	0	2				
38	*Sorites marginalis*					0	2	0	1	0	1										
39	*Peneroplis planatus*							0	1	0	1										
40	*Lagena striata*									0	2									0	2
41	*Bolivina nobilis*							0	1	1	5									0	1
42	*Bolivina striatula*							0	1												

43	*Cancris auriculus*					0	2	0	2												
44	*Eponides repandus*					0	2	0	1												
45	*Rosalina globularis*	0	8	2	7	1	9	1	11	2	12			0	4	0	2	2	5	2	4
46	*Discorbinella bertheloti*			0	2																
47	*Cibicides lobatulus*	0	2	2	12	0	2	0	4									0	1	0	1
48	Cassidulina laevgata							0	1												
49	*Cymbaloporetta bradyi*	0	1															0	1		
50	*Amphistegina lessonii*					0	1	0	1									0	2	0	1
51	*Amphistegina radiata*					0	12	2	24	1	17								0	1	0
52	*Nonionellina labradorica*	0	3	0	4	0	2														
53	*Nonionoides boueanum*	0	2																		
54	*Nonionoides elongatum*			0	5			0	3												
55	*Peneroplis planatus*			0	1							0	1	0	2						
56	*Pararotalia calcar*	0	22	2	17	1	28	1	18			0	7	0	5	2	18	1	24	2	17
57	*Pararotalia nipponica*	2	28	6	68	12	150	25	164	12	102	0	12	2	41	1	24	2	14	2	14
58	*Ammonia beccarii*	3	68	6	92	21	290	4	28	12	159	1	18	2	16	2	154	2	174	1	79
59	*Ammonia dentata*	1	12	0	4	0	3	0	4	0	14	1	8	0	10	2	18	2	24	2	17
60	*Ammonia tepida*	1	10	0	2	0	2	0	4	0	8	2	24	2	112	7	141	2	54	1	75
61	*Asterorotalia inflata*															0	1	0	2		
62	*Asterorotalia trispinosa*					0	4	0	2												
63	*Pseudorotalia schroeteriana*			0	3	0	1							0	2						
64	*Edentostomina cultrata*					0	2														
65	*Elphidium advenum*	0	2					0	4			0	2								
66	*Elphidium craticulatum*					0	2					0	2								
67	*Elphidium crispum*	0	0	1	14	2	14	0	1	0	4	0	4	0	11	2	15	2	14	1	21
68	*Elphidium discoidale*	0	4	0	2	0	1	0	2	0	1	1	2	0	1	0	1	0	2	0	4
69	*Elphidium incertum*	0	3									0	3	1	5	0	3	0	2	0	4
70	*E.excavatum*					0	1	0	1	0	1					0	1	0	1		
71	*E.macellum*					0	1	0	1	0	1					0	4	0	1		
72	*Elphidium sp1*																				
73	*Elphidium sp2*																				
74	*Parrellina hispidula*	0	1	0	1							0	1								
75	*Rectobolivina Raphanus*			0	3			0	1	0	1			0	2	0	1				
76	*Asrilina ammonoides*			0	3	1	5	4	26	2	12							0	2	0	1
77	*Osangularia venusta*	0	12	0	17	2	26	1	48	2	62	2	141	12	120	2	17	21	147	5	75
	TOTAL	7	**226**	24	**369**	44	**657**	43	**458**	34	**88**	7	**247**	19	**350**	18	**425**	35	**487**	18	**327**
	Number of Genus	*2*	*16*	*7*	*25*	*8*	*25*	*10*	*28*	*9*	*11*	*3*	*13*	*4*	*15*	*4*	*19*	*6*	*12*	*5*	*13*
	Individual species	*4*	*34*	*10*	*41*	*10*	*45*	*12*	*48*	*9*	*32*	*5*	*24*	*5*	*24*	*6*	*28*	*8*	*24*	*10*	*21*

43	*Cancris auriculus*										
44	*Eponides repandus*										
45	*Rosalina globularis*	0	2	1	5	0	4	0	2	0	3
46	*Discorbinella bertheloti*	0	2	0	1						
47	*Cibicides lobatulus*			0	3					0	2
48	Cassidulina laevigata										
49	*Cymbaloporetta bradyi*										
50	*Amphistegina lessonii*	1									
51	*Amphistegina radiata*	0	6	0	9			0	1	1	8
52	*Nonionellina labradorica*		3	0	2			0	1	0	2
53	*Nonionoides boueanum*		2	0	3	0	3	0	2	1	4
54	*Nonionoides elongatum*		48	5	22	4	24	4	47	14	41
55	*Pyneropsis planatus*										
56	*Pararotalia calcar*										
57	*Pararotalia nipponica*	0	24	0	12	1	6			0	2
58	*Ammonia beccarii*	7	20	6	26	2	12			2	18
59	*Ammonia dentata*	3	38	5	33	4	34	3	54	3	34
60	*Ammonia tepida*	4	48	6	32	6	41	2	78	4	54
61	*Asterorotalia inflata*			0	6	0	4			1	6
62	*Asterorotalia trispinosa*										
63	*Pseudorotalia schroeteriana*	0	1	0	2						
64	*Edentostomina cultrata*										
65	*Elphidium advenum*										
66	*Elphidium craticulatum*										
67	*Elphidium crispum*			0	1	0	2			0	1
68	*Elphidium discoidale*										
69	*Elphidium incertum*										
70	*E.excavatum*										
71	*E.macellum*										
72	*Elphidium sp1*	0	2	0	1						
73	*Elphidium sp2*										
74	*Parrellina hispidula*					1	5			0	1
75	*Rectobolivina Raphanus*			0	2						
76	*Anomalina ammonoides*	0	1	0	1	1	8				
77	*Osangularia venusta*	5	14	1	15	0	14	0	12	0	15
	TOTAL	21	263	28	236	22	204	11	233	27	219
	Number of Genus	*4*	*7*	*7*	*24*	*8*	*14*	*4*	*13*	*6*	*15*
	Individual species	*6*	*26*	*9*	*38*	*10*	*31*	*5*	*16*	*9*	*24*

43	*Cancris auriculus*										
44	*Eponides repandus*										
45	*Rosalina globularis*	0	2	1	5	0	4	0	2	0	3
46	*Discorbinella bertheloti*	0	2	0	1						
47	*Cibicides lobatulus*			0	3					0	2
48	Cassidulina laevigata										
49	*Cymbaloporetta bradyi*										
50	*Amphistegina lessonii*	1									
51	*Amphistegina radiata*	0	6	0	9			0	1	1	8
52	*Nonionellina labradorica*		3	0	2			0	1	0	2
53	*Nonionoides boueanum*		2	0	3	0	3	0	2	1	4
54	*Nonionoides elongatum*		48	5	22	4	24	4	47	14	41
55	*Pyneropsis planatus*										
56	*Pararotalia calcar*										
57	*Pararotalia nipponica*	0	24	0	12	1	6			0	2
58	*Ammonia beccarii*	7	20	6	26	2	12			2	18
59	*Ammonia dentata*	3	38	5	33	4	34	3	54	3	34
60	*Ammonia tepida*	4	48	6	32	6	41	2	78	4	54
61	*Asterorotalia inflata*			0	6	0	4			1	6
62	*Asterorotalia trispinosa*										
63	*Pseudorotalia schroeteriana*	0	1	0	2						
64	*Edentostomina cultrata*										
65	*Elphidium advenum*										
66	*Elphidium craticulatum*										
67	*Elphidium crispum*			0	1	0	2			0	1
68	*Elphidium discoidale*										
69	*Elphidium incertum*										
70	*E.excavatum*										
71	*E.macellum*										
72	*Elphidium sp1*	0	2	0	1						
73	*Elphidium sp2*										
74	*Parrellina hispidula*					1	5			0	3
75	*Rectobolivina Raphanus*			0	2						
76	*Assilina ammonoides*	0	1	0	1	1	8				
77	*Osangularia venusta*	5	14	1	15	0	14	0	12	0	15
	TOTAL	21	263	28	236	22	204	11	233	27	219
	Number of Genus	*4*	*7*	*7*	*24*	*8*	*14*	*4*	*13*	*6*	*15*
	Individual species	*6*	*26*	*9*	*38*	*10*	*31*	*5*	*16*	*9*	*24*

Table.7.1 Distribution of living and total foraminifera between Mandapam and Tuticorin (Offshore)

S	Station Numbers	Vaippar										Kallar									
	Depth in mts	2m		3m		4m		5m		7m		2m		4m		6m		7m		7.5m	
	Name of Species	L	T	L	T	L	T	L	T	L	T	L	T	L	T	L	T	L	T	L	T
1	*Ammobaculites exiguus*	0	1	0	2	0	1	0	2	0	1										
2	*Textularia agglutinans*					0	3	0	3			0	2	0	1	0	4	0	1		
3	*Textularia conica*			0	2		4														
4	*Vertebralina striata*	0	2			0	2	0	1			0	2	0	1						
5	*Edentostomina cultrata*	0	1									0	2	0	2	0	1			0	1
6	*Adelosina laevigata*	0	1	0	1	0	2	0	1	0	3					0	3	0	2		
7	*Spiroloculina aequa*	0	1	0	2	0	1														
8	*Spiroloculina affixa*	0	1							0	1										
9	*Spiroloculina communis*	1	2	0	4	1	6	0	5	1	9	0	3	0	2	1	5				
10	*Spiroloculina costifera*			0	4	0	6			0	3							0	1	0	1
11	*Spiroloculina depressa*			0	1	0	2														
12	*Spiroloculina orbis*			0	1	0	2	1	2												
13	*Spiroloculina sp 1*	0	2																		
14	*Spiroloculina sp 2*																				
15	*Massilina secans tropicalis*	0	2	0	1	0	1														
16	*Vertebralina striata*																				
17	*Quinqueloculina agglutinans*	0	2	0	1	0	2	1	2	0	1	0	2			0	2				
18	*Quinqueloculina bicostata*											0	4	0	3	0	2				
19	*Quinqueloculina costata*																				
20	*Quinqueloculina elegans*																				
21	*Quinqueloculina lamarckiana*	0	2	0	2	0	1			0	2	0	4	1	6		3	0	2	1	2
22	*Quinqueloculina polygona*	0	1			0	2			0	1	1	6	1	4		2	0	1		
23	*Quinqueloculina seminulum*	0	4	2	8	0	2	1	8	0	2	0	3	0	2	0	1	0	8		
24	*Quinqueloculina elongatum*	0	4	0	7	0	1			0	2										
25	*Quinqueloculina tropicalis*	0	2	0	7	1	4			0	4										
26	*Quinqueloculina sp 1*	0	1																		
27	*Quinqueloculina sp 2*																				
28	*Miliolinella circularis*	0	1	0	2	0	1			0	1	0	2	0	1	0	2				
29	*Triloculina oblonga*																				
30	*Triloculina insignis*	0	2	0	2	0	1														
31	*Triloculina schreiberiana*	0	1	1	9																
32	*Triloculina terquemiana*					0	2														
33	*Triloculina tricarinata*	0	2	1	7	0	8	0	1	2	12	2	12	2	14	0	8	1	11		
34	*Triloculina trigonula*	1	8	2	12	2	16	0	1	2	28	1	8	0	5	0	4	0	8		
35	*Hauerina bradyi*																				
36	*Articulina pacifica*																				
37	*Rupertianella rupertiana*	0	1							0	4	0	5	0	1			0	1		
38	*Sorites marginalis*	0	1																		
39	*Peneroplis planatus*																				
40	*Lagena striata*					0	1			0	2			0	2	0	1	0	4		
	Bolivina mobilis																				
41	*Brizalina striatula*																				
42	*Cancris auriculus*																				
43	*Eponides repandus*					0	2			0	1										

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44	*Bolivina globularis*	0	2									0	6	0	17	0	5	0	2		
45	*Discorbinella bertheloti*					0	2														
46	*Cibicides lobatulus*	0	1	0	2	0	2			0	4	0	1	0	1			0	2		
47	Cassidulina laevigata																				
48	*Cymbaloporetta bradyi*	0	1																		
	Amphistegina lessonii																				
49	*Amphistegina radiata*	2	12	2	24	0	2			2	10		3	0	4	0	8	0	5		
50	*Nonionellina labradorica*	0	1	0	2	1	2					1	11	0	1						
51	*Nonionoides boueanum*	0	2	0	3									0	2	0	1				
52	*Nonionoides elongatum*			2	12	1	4			0	3	3	16	2	12	0	3	0	7		
	Peneroplis planatus																				
54	*Pararotalia calcar*	0	2																		
55	*Pararotalia nipponica*	0	3	0	2								8	0	4						
56	*Ammonia beccarii*	1	20	7	91	21	187	18	210	18	108	3	28	12	137	11	108	14	122	15	101
57	*Ammonia domata*	1	6	2	12	0	4	0	1	1	7	2	14	4	24	4	35	3	24	2	18
58	*Ammonia tepida*	3	11	1	4	0	3					2	24	8	65	4	32	3	28		
59	*Asterorotalia inflata*	1	2	0	2	0	4	0	1	1	3	0	6	0	7	1	7	0	2		
60	*Asterorotalia trispinosa*					0	2			0	1										
61	*Pseudorotalia schroeteriana*			0	2	0	2					0	2								
62	*Cribrononion simplex*			0	1	0	2														
63	*Elphidium advenum*			0	3							0	2	0	1						
64	*Elphidium craticulatum*			0	3	0	2														
65	*Elphidium crispum*	1	8	1	7	1	7	0	1	2	10	0	14	2	28	2	19	2	25	2	14
66	*Elphidium discoidale*	1	5	1	4	0	2					0	4	0	3	0	3	0	1		
67	*Elphidium incertum*	0	3	0	1							0	2	0	1	0	1				
68	*E.excavatum*																				
69	*E.macellum*																				
70	*Elphidium sp 1*			0	1																
71	*Elphidium sp 2*	0	1																		
72	*Parrellina hispidula*	0	1	0	1							0	2	0	8	1	6	0	4		
73	*Rectobolivina Raphanus*			0	2					0	1										
74	*Asilina ammonoides*					0	4	0	3	0	2	0	2	0	2	0	3	0	2	0	1
75	*Quangularia venusta*	12										2	124	4	248	2	286	2	257	3	334
	TOTAL	12	126	22	239	28	306	21	241	29	226	17	322	16	613	26	555	25	520	25	492
	Number of Genus	*6*	*20*	*6*	*17*	*6*	*18*	*3*	*10*	*6*	*17*	*5*	*19*	*6*	*18*	*6*	*16*	*4*	*13*	*5*	*8*
	Individual species	*9*	*40*	*11*	*37*	*7*	*39*	*4*	*15*	*8*	*30*	*9*	*31*	*9*	*31*	*8*	*27*	*6*	*16*	*6*	*16*

Table.7.1 Distribution of living and total foraminifera between Mandapam and Tuticorin (Offshore)

S	Station Numbers	Tuticorin									
	Depth in mts	2m		3m		4m		5m		6m	
	Name of Species	L	T	L	T	L	T			L	T
1	*Ammobaculites exiguus*										
2	*Textularia agglutinans*							0	4	0	5
3	*Textularia conica*							0	2	0	4
4	*Vertebralina striata*					0	1	0	2	0	1
5	*Edentostomina cultrata*										
6	*Adelosina laevigata*					0	9				
7	*Spiroloculina angusta*					0	3			0	4
8	*Spiroloculina affixa*										
9	*Spiroloculina communis*	0	4	0	12	1	6			0	8
10	*Spiroloculina costifera*	0	1	0	2	0	2	0	1	0	3
11	*Spiroloculina depressa*			0	2	0	1				
12	*Spiroloculina orbis*			0	3	0	4	0	1	1	24
13	*Spiroloculina sp 1*										
14	*Spiroloculina sp 2*			0	1						
15	*Massilina secans tropicalis*										
16	*Vertebralina striata*										
17	*Quinqueloculina agglutinans*			0	3	0	3	0	5	0	2
18	*Quinqueloculina bicostata*			0	6	1	7			1	12
19	*Quinqueloculina costata*										
20	*Quinqueloculina elegans*					0	2			0	2
21	*Quinqueloculina lamarckiana*	3	56	2	47	0	4	1	8		
22	*Quinqueloculina polygona*					0	2	0	4	0	2
23	*Quinqueloculina seminulum*			0	2	0	2	0	1	1	12
24	*Quinqueloculina elongatum*										
25	*Quinqueloculina tropicalis*			0	7						
26	*Quinqueloculina sp 1*										
27	*Quinqueloculina sp 2*										
28	*Miliolinella circularis*										
29	*Triloculina oblonga*							0	1	0	1
30	*Triloculina insignis*	0	3	0	4	0	2	0	1	0	1
31	*Triloculina schreiberiana*	0	6	0	5	0	3	0	1	0	3
32	*Triloculina terquemiana*	0	4	0	28	0	8	0	7	0	2
33	*Triloculina tricarinata*					0	4	1	5	0	5
34	*Triloculina trigonula*	1	5	2	19	2	6	2	8	0	10
35	*Hauerina bradyi*	0	2	0	2	0	4	0	1	0	1
36	*Articulina pacifica*	0	2	0	1						
37	*Rupertianella rupertiana*	0	3					0	1		
38	*Sorites marginalis*	0	1					0	2		
39	*Peneroplis planatus*			0	1	0	2				
40	*Lagena striata*									0	1
	Bolivina nobilis										
41	*Brizalina striatula*										
42	*Cancris auriculus*					0	1				

43	*Eponides repandus*					0	2				
44	*Rosalina globularis*										
45	*Discorbinella bertheloti*			0	1	0	2				
46	*Cibicides lobatulus*	0	2	1	4	0	2	0	4	1	8
47	Cassidulina laevigata										
48	*Cymbaloporetta bradyi*										
	Amphistegina lessonii										
49	*Amphistegina radiata*	0	1	0	2	0	3			0	5
50	*Nonionellina labradorica*										
51	*Nonionoides boueanum*					0	3			0	2
52	*Nonionoides elongatum*	0	1	0	1						
	Peneroplis planatus										
54	*Pararotalia calcar*	0	12	2	15	5	45	2	14	3	28
55	*Pararotalia nipponica*	1	34	3	47	2	12	2	18	2	14
56	*Ammonia beccarii*	3	18	0	2	1	4	5	58	11	42
57	*Ammonia dentata*	0	2	1	8	8	48	2	18	20	98
58	*Ammonia tepida*	0	4	0	8	1	12	5	17	0	2
59	*Asterorotalia inflata*	2	26	0	3	1	4	0	1	12	58
60	*Asterorotalia trispinosa*					0	2	0	4	0	2
61	*Pseudorotalia schroeteriana*										
62	*Cribrononion simplex*				1	0	2				
63	*Elphidium advenum*	1	12	3	14	1	12			0	3
64	*Elphidium craticulatum*	1	8	0	8	0	2			0	1
65	*Elphidium crispum*	1	4	0	4	2	5	0	4	0	5
66	*Elphidium discoidale*		2			0	1				
67	*Elphidium incertum*					0	2				
68	*E.excavatum*										
69	*E.macellum*							0	1	0	2
70	*Elphidium sp 1*										
71	*Elphidium sp 2*										
72	*Parrellina hispidula*					0	1			0	2
73	*Rectobolivina Raphanus*										
74	*Assilina ammonoides*	0	4	0	15	0	12	1	12	1	12
75	*Operculina venosa*	0	4	1	11	2	14	2	18	1	15
	TOTAL	13	**221**	15	**281**	27	**268**	**23**	**224**	54	**402**
	Number of Genus	*11*	*12*	*11*	*22*	***8***	*20*	***6***	*16*	***8***	*18*
	Individual species	*17*	*27*	*23*	*33*	***11***	*42*	***10***	*30*	***11***	*37*

	Post tsunami species		Pre-tsunami species
41	*Bolivina nobilis*	41	*Siphonina philippinensis*
42	*Brizalina striatula*	42	*Sorites marginalis*
43	*Cancris auriculus*	43	*Spirolina arietinus*
44	*Eponides repandus*	44	*Spiroloculina communis*
45	*Rosalina globularis*	45	*S. costifera*
46	*Discorbinella bertheloti*	46	*Textularia agglutinans*
47	*Cibicides lobatulus*	47	*T.aura*
48	*Cassidulina laevgata*	48	*T.conica*
49	*Cymbaloporetta bradyi*	49	*T.pseudotrochus*
50	*Amphistegina lessonii*	50	*Triloculina oblonga*
51	*Amphistegina radiata*	51	*T.schreberiana*
52	*Nonionellina labradorica*	52	*T.terquemiana*
53	*Nonionoides boueanum*	53	*T.tricarinata*
54	*Nonionoides elongatum*	54	*T.trigonuia*
55	*Peneroplis planatus*	55	*Uvigerina hispido-costana*
56	*Pararotalia calcar*	56	*Vertebralina striata*
57	*Pararotalia nipponica*	57	*Globigerina bulloides*
58	*Ammonia beccarii*	58	*Globigerinoides trilobus*
59	*Ammonia dentata*	59	*Globorotalia mennardii*
60	*Ammonia tepida*	60	*A.dentata*
61	*Asterorotalia inflata*	61	*E.hispidulum*
62	*Asterorotalia trispinosa*	62	*F.labradoricum*
63	*Pseudorotalia schroeteriana*	63	*Glabratella australensis*
64	*Edentostomina cultrata*	64	*Globigerinodes trilobus*
65	*Elphidium advenum*	65	*Haplophragmoides emaciatum*
66	*Elphidium craticulatum*	66	*Miliolinella circularis*
67	*Elphidium crispum*	67	*orbulina universa*
68	*Elphidium discoidale*	68	*pseudomassilina macilenta*
69	*Elphidium incertum*	69	*Q.bicostata*
70	*E.excavatum*	70	*R.virgula*
71	*E.macellum*	71	*Reussella spinulosa*
72	*Elphidium.sp1*	72	*Rupertianella rupertiana*
73	*Elphidium.sp2*	73	*Sorites orbiculus*
74	*Parrellina hispidula*	74	*S.orbis*
75	*Rectobolivina Raphanus*	75	*Triloculina terquemiana*
76	*Assilina ammonoides*	76	*Assilina ammonoides*
77	*Osangularia venusta*	77	*Osangularia venusta*

Table. 3. Comparison of Pre-tsunami and Post- tsunami foraminiferal species in the study area

Post tsunami species		Pre-tsunami species
Ammobaculites exiguus	1	*Alveolinella quoyi*
Textularia agglutinans	2	*Ammonia beccarii*
Textularia conica	3	*A.beccarii var.tepida*
Vertebralina striata	4	*Amphistegina lessonii*
Edentostomina cultrata	5	*Buliminella millettii*
Adelosina laevigata	6	*Cassidulina laevgata*
Spiroloculina aequa	7	*Chrysalidinella dimorpha*
Spiroloculina affixa	8	*Cibicides lobatulus*
Spiroloculina communis	9	*C.refulgens*
Spiroloculina costifera	10	*Elphidium crispum*
Spiroloculina depressa	11	*E.crispum var.crassa*
Spiroloculina orbis	12	*E.excavatum*
Spiroloculina sp1	13	*E.incertum*
Spiroloculina sp2	14	*E,macellum*
Massilina secans tropicalis	15	*Fissurina bod jonegoroensis*
Vertebralina striata	16	*Florilus boueanus*
Quinqueloculina agglutinans	17	*F.grateloupi*
Quinqueloculina bicostata	18	*Hauerina bradyi*
Quinqueloculina costata	19	*H.fragilissima*
Quinqueloculina elegans	20	*H.involuta*
Quinqueloculina lamarckiana	21	*Heterostegina suborbcularis*
Quinqueloculina polygona	22	*Lagena striata*
Quinqueloculina seminulum	23	*Operculina ammoides*
Quinqueloculina elongatum	24	*Opercullinella cumingii*
Quinqueloculina tropicalis	25	*O. venosus*
Quinqueloculina sp 1	26	*Osangulariria vemata*
Quinqueloculina sp 2	27	*Peneroplis planatus*
Miliolinella circularis	28	*Planorbulinalla mediterranensis*
Triloculina oblanga	29	*Planorbulinella larvata*
Triloculina insignis	30	*Poroeponides lateralis*
Triloculina schreiberiana	31	*Pseudotriioculina rupertiana*
Triloculina terquemiana	32	*Pyrgo subsphaertica*
Triloculina tricarinata	33	*Quinqueloculina agglutinans*
Triloculina trigonula	34	*Q.inca*
Hauerina bradyi	35	*Q.lamarckiana*
Articulina pacifica	36	*Q.polygona*
Rupertianella rupertiana	37	*Q.pseudoreticulata*
Sorites marginalis	38	*Q.undulose-costata*
Peneroplis planatus	39	*Rectobolivina-raphanus*
Lagena striata	40	*Sigmavirgulina tortuosa*

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