BHARATHIDASAN UNIVERSITY

Tiruchirappalli- 620024
Tamil Nadu, India

Programme : M.Tech., Geological Technology and Geoinformatics

Course Title : Geoinformatics in Disaster Management
Course Code : MTIGT0704

Unit-3: Coastal Disasters

Dr. J. SARAVANAVEL
Professor, Department of Remote Sensing
Bharathidasan University
Tiurchirappalli, Tamil Nadu
Email : drsaraj@gmail.com, saravanavel@bdu.ac.in

Unit:3. Coastal disasters: Tsunami: Causes of Tsunami - Characteristics of Tsunami wave, velocity and speed of Tsunami - Tsunami generation belts of world - Historical Tsunami inundation - Causes of 26th December 2004 Indian Ocean Tsunami - Tsunami propagation and inundation models: Method of Splitting Tsunami (MOST) Model - tsunami inundation and run up mapping - offshore configuration vs tsunami run up - coastal geomorphology and geometry vs tsunami inundation - Mitigation strategies. Other Coastal Hazards: Coastal Erosion - Saltwater intrusion - Global warming and Sea level rise - Tropical cyclone Storm surges - Remote Sensing and GIS based coastal vulnerability mapping.

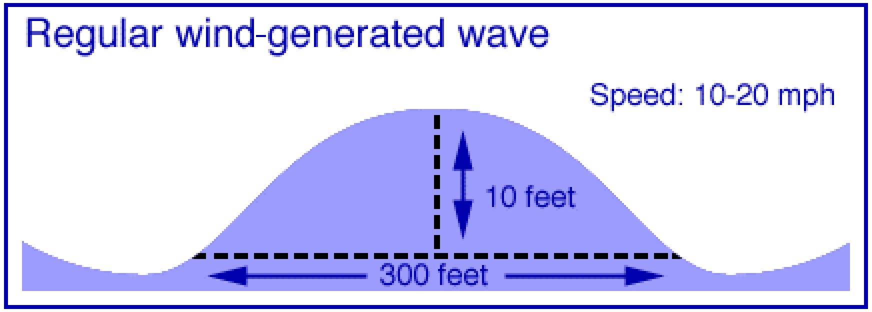
Remote Sensing and GIS in Tsunami Disasters

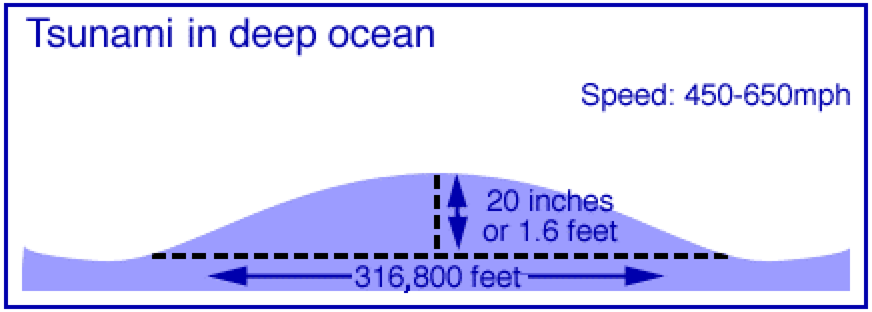
“The great wave off the coast of Kanagawa”
a famous picture by the Japanese artist
Hokusai (1823-1829)

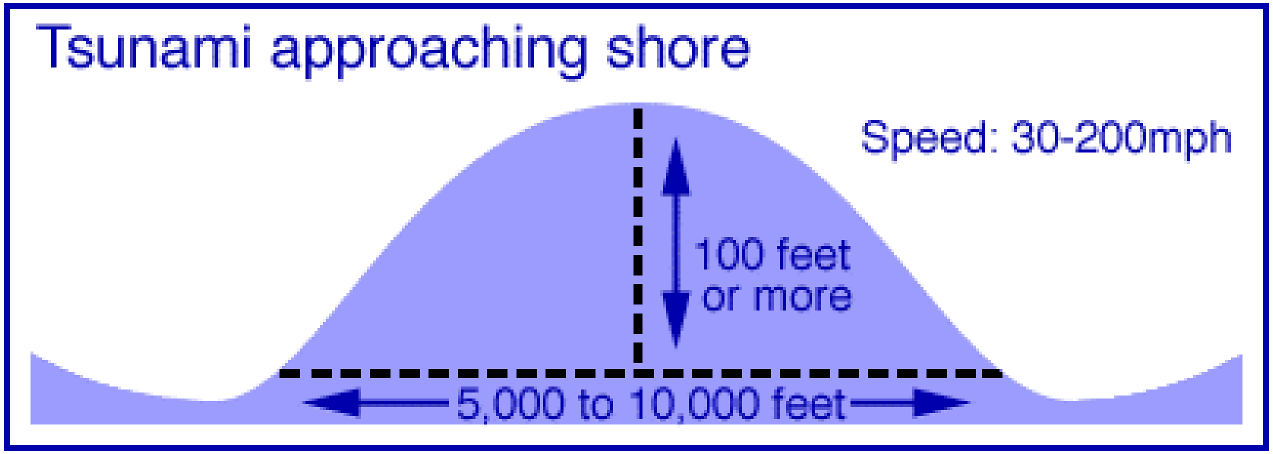
A **tsunami** (pronounced soo-NAA-mee) is a series of waves (called a "wave train") generated in a body of water by a abrupt disturbance that vertically displaces the water column.

Lisbon, Portugal Tsunami of 1755

The phenomenon we call a tsunami is a series of waves of extremely long wavelength and period generated in a body of water by an impulsive disturbance that displaces the water. Although tsunamis are often referred to as "tidal waves" by English-speaking people, they are not caused by the tides and are unrelated to them.





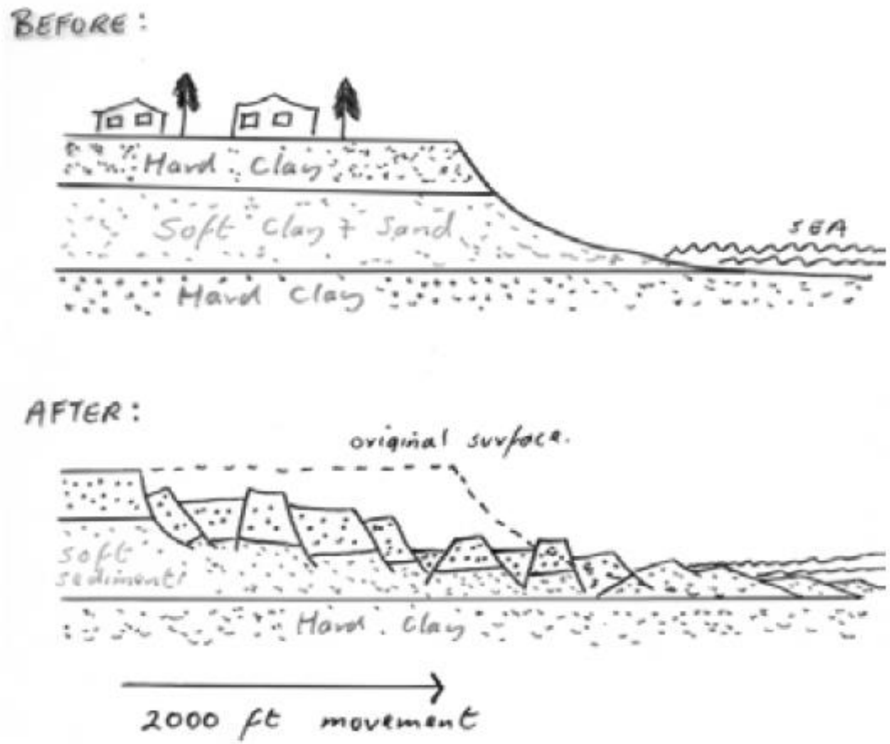


HOW TSUNAMIS ARE CAUSED ?

- **Huge submarine Earthquakes**
- **Submarine landslides**
- **Submarine volcanic eruptions**
- **Fall of huge sheets of ice**
- **Fall of giant meteorites**

Most prominent are the Earthquake triggered Tsunamis

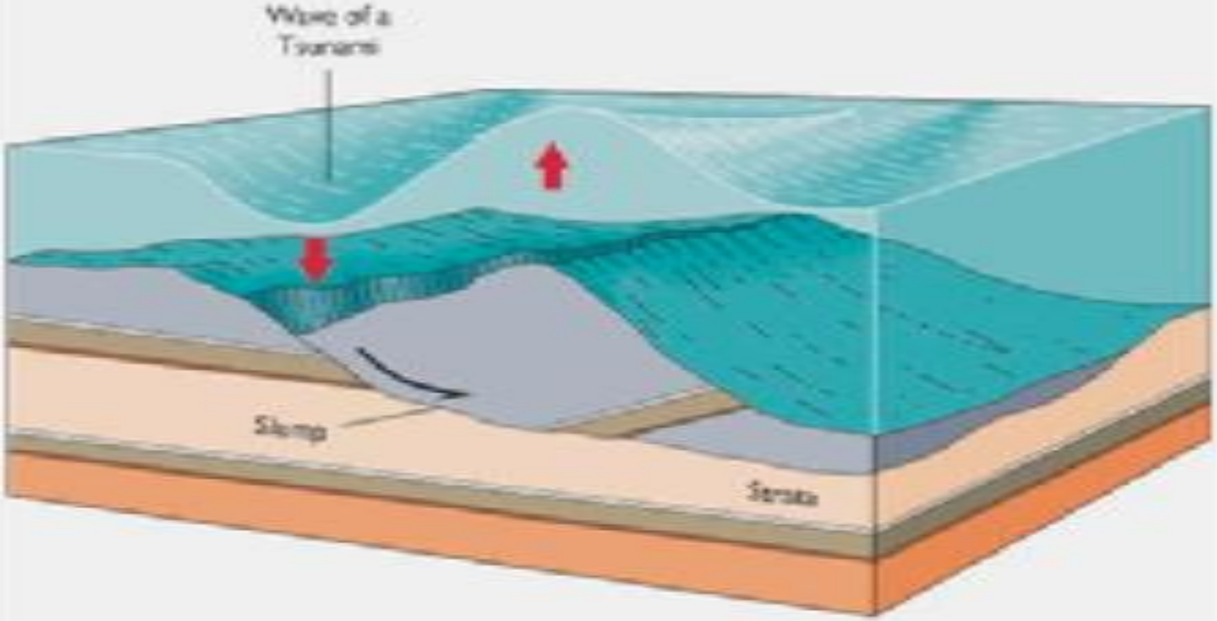
Landslide at Turnagain Heights, Alaska, 1964



A very good example of liquefaction

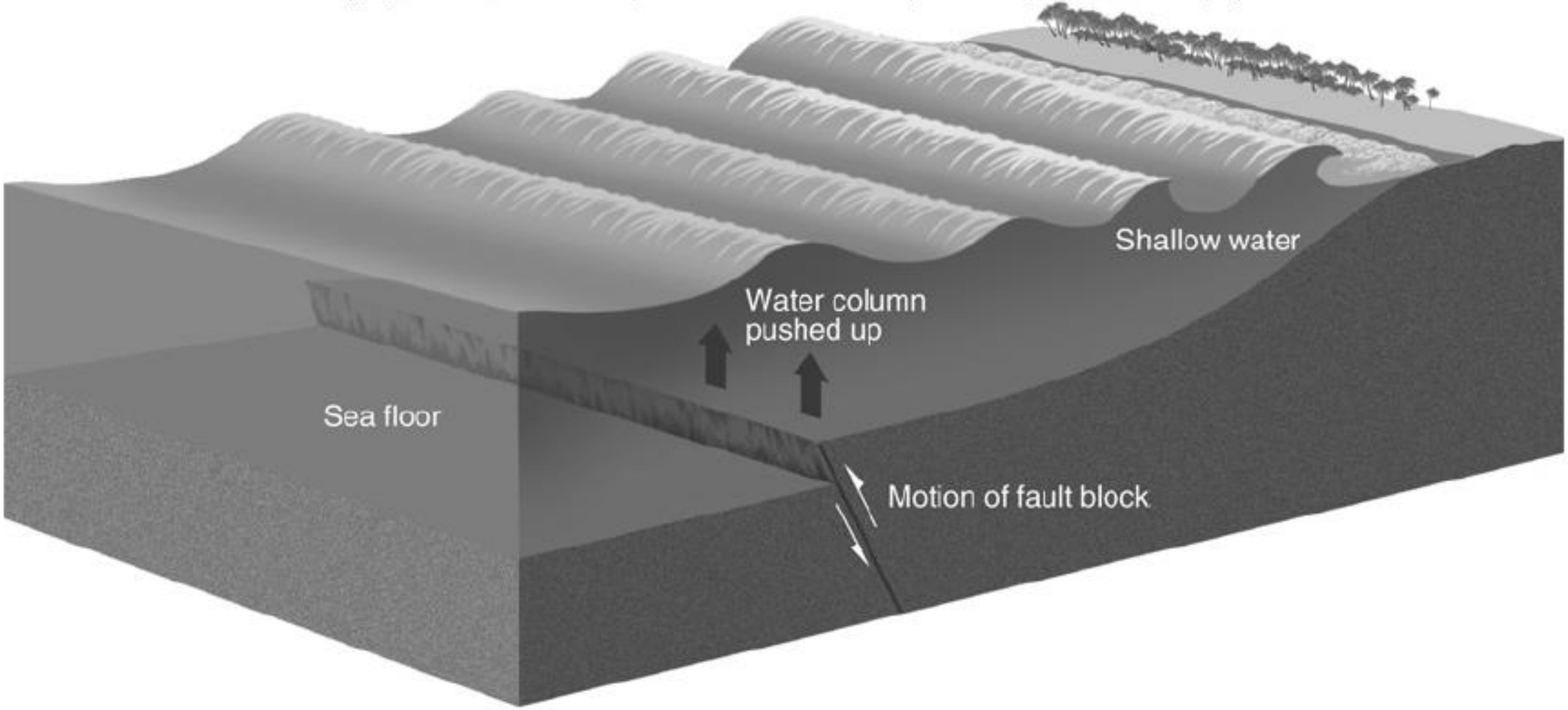
Slumping of a large mass of sediment disturbs the overlying water surface and produces a series of flat, long-period waves.

Figure 7.13a



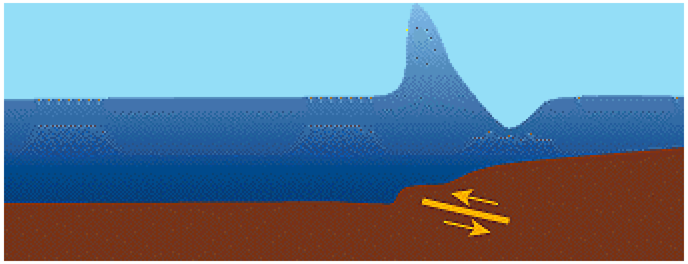
(a) GENERATION OF A TSUNAMI

Generation of a Tsunami by Faulting



Characteristics

- Move at high speeds
- Can travel enormous distances with little energy loss
- Can cause damage thousands of miles from its origin
- May be several hours between its creation and its impact on the coast

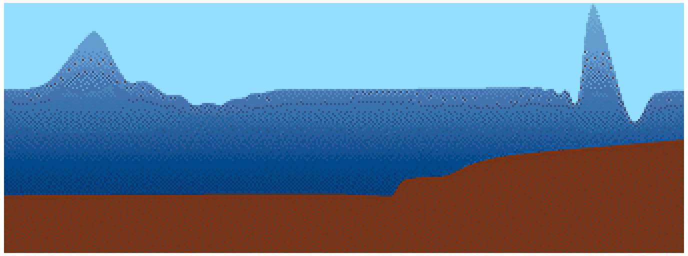


Panel 1--Initiation: Earthquakes are commonly associated with ground shaking that is a result of elastic waves traveling through the solid earth. However, near the source of submarine earthquakes, the seafloor is "permanently" uplifted and down-dropped, pushing the entire water column up and down. The potential energy that results from pushing water above mean sea level is then transferred to horizontal propagation of the tsunami wave (kinetic energy). For the case shown above, the earthquake rupture occurred at the base of the continental slope in relatively deep water. Situations can also arise where the earthquake rupture occurs beneath the continental shelf in much shallower water.

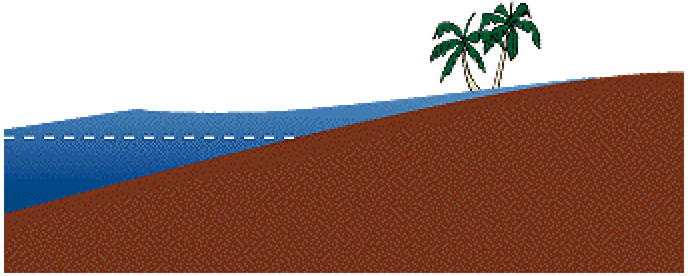
Note: In the figure the waves are greatly exaggerated compared to water depth! In the open ocean, the waves are at most, several meters high spread over many tens to hundreds of kilometers in length.

Panel 2--Split: Within several minutes of the earthquake, the initial tsunami (Panel 1) is split into a tsunami that travels out to the deep ocean (distant tsunami) and another tsunami that travels towards the nearby coast (local tsunami).The height above mean sea level of the two oppositely traveling tsunamis is approximately half that of the original tsunami (Panel 1). (This is somewhat modified in three dimensions, but the same idea holds.)

The speed at which both tsunamis travel varies as the square root of the water depth. Therefore the deep-ocean tsunami travels faster than the local tsunami near shore.

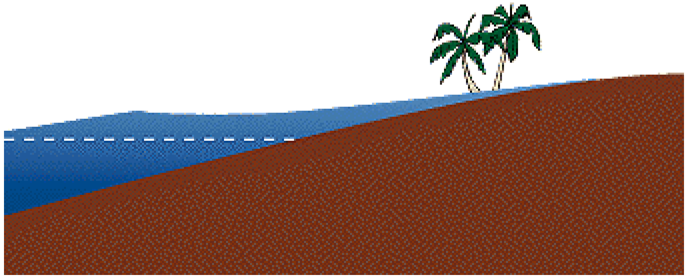


Panel 3--Amplification: Several things happen as the local tsunami travels over the continental slope. Most obvious is that the amplitude increases. In addition, the wavelength decreases. This results in steepening of the leading wave--an important control of wave run-up at the coast (next panel).Note also that the deep ocean tsunami has traveled much farther than the local tsunami because of the higher propagation speed. As the deep ocean tsunami approaches a distant shore, amplification and shortening of the wave will occur, just as with the local tsunami shown above.



Panel 4—Runup: As the tsunami wave travels from the deep-water, continental slope region to the near-shore region, tsunami run-up occurs. Run-up is a measurement of the height of the water onshore observed above a reference sea level.

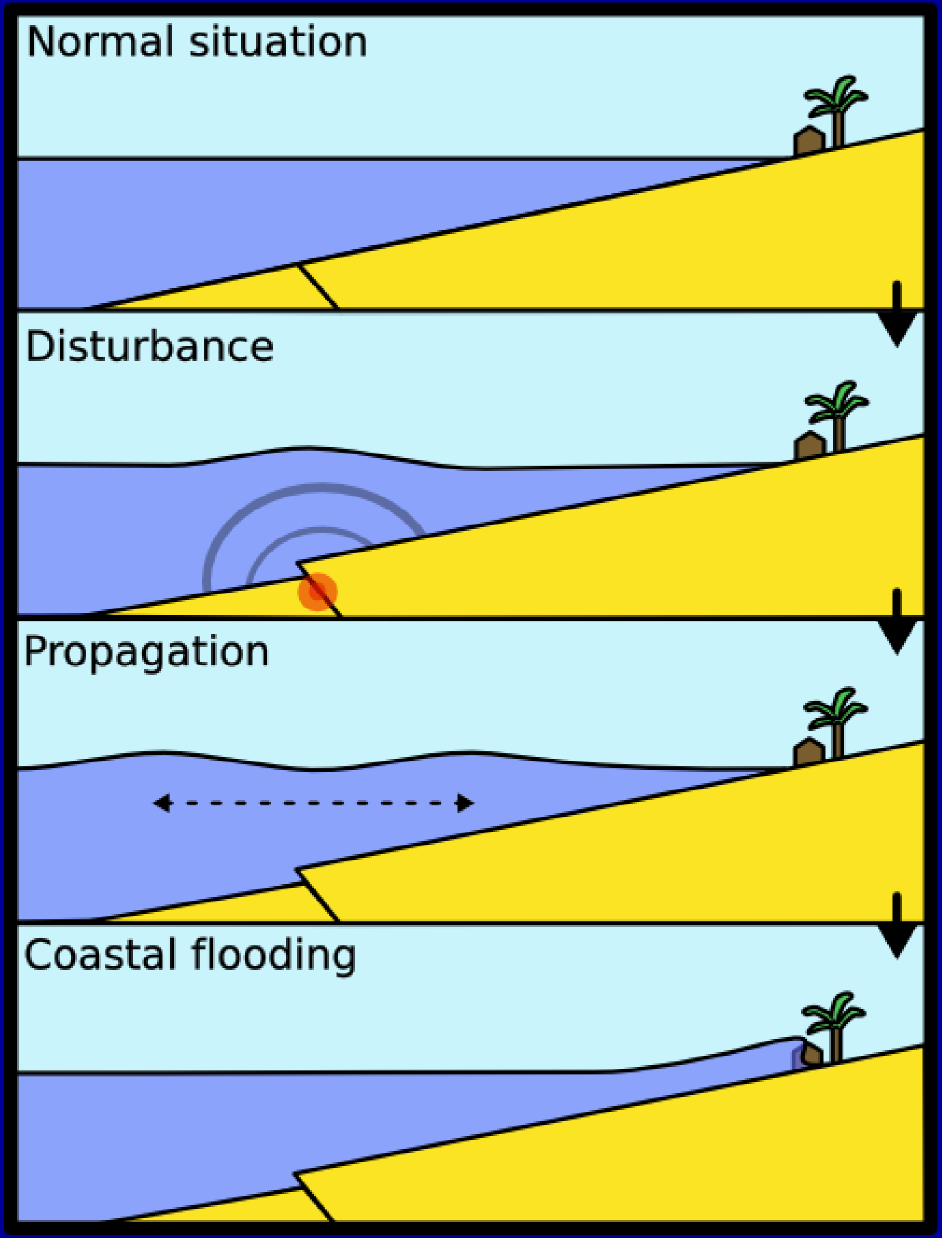
Contrary to many artistic images of tsunamis, most tsunamis do not result in giant breaking waves (like normal surf waves at the beach that curl over as they approach shore). Rather, they come in much like very strong and very fast tides (i.e., a rapid, local rise in sea level). Much of the damage inflicted by tsunamis is caused by strong currents and floating debris. The small number of tsunamis that do break often form vertical walls of turbulent water called bores. Tsunamis will often travel much farther inland than normal waves.



Do tsunamis stop once on land? After run-up, part of the tsunami energy is reflected back to the open ocean.

In addition, a tsunami can generate a particular type of wave called edge waves that travel back-and forth, parallel to shore.

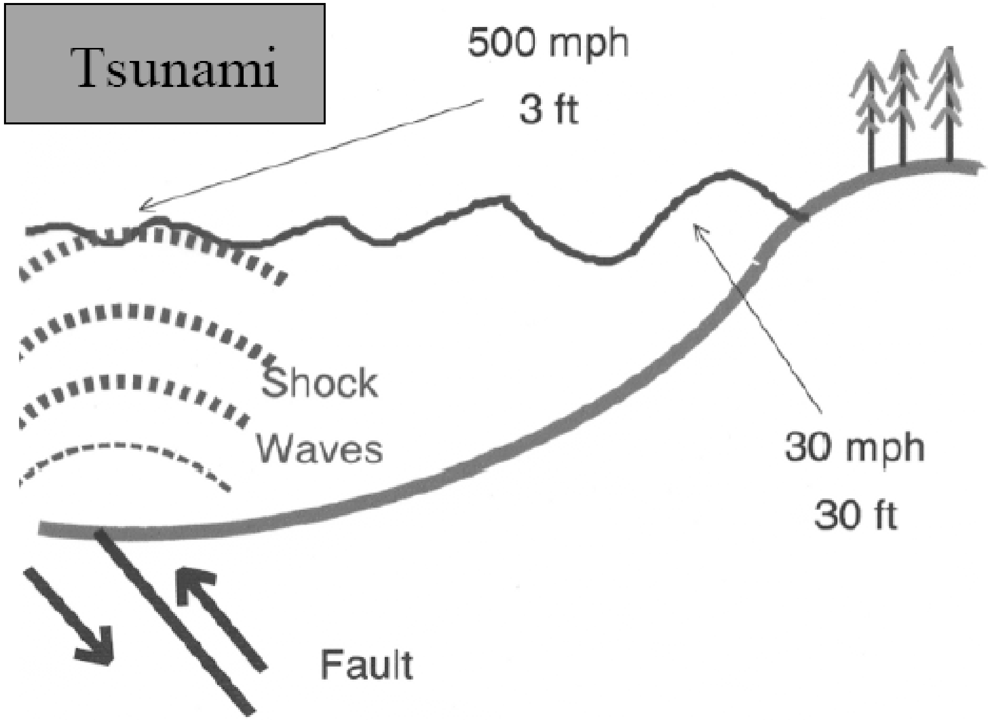
These effects result in many arrivals of the tsunami at a particular point on the coast rather than a single wave suggested by above. Because of the complicated behavior of tsunami waves near the coast, the first run-up of a tsunami is often not the largest, emphasizing the importance of not returning to a beach several hours after a tsunami hits.



Tsunamis are created when:

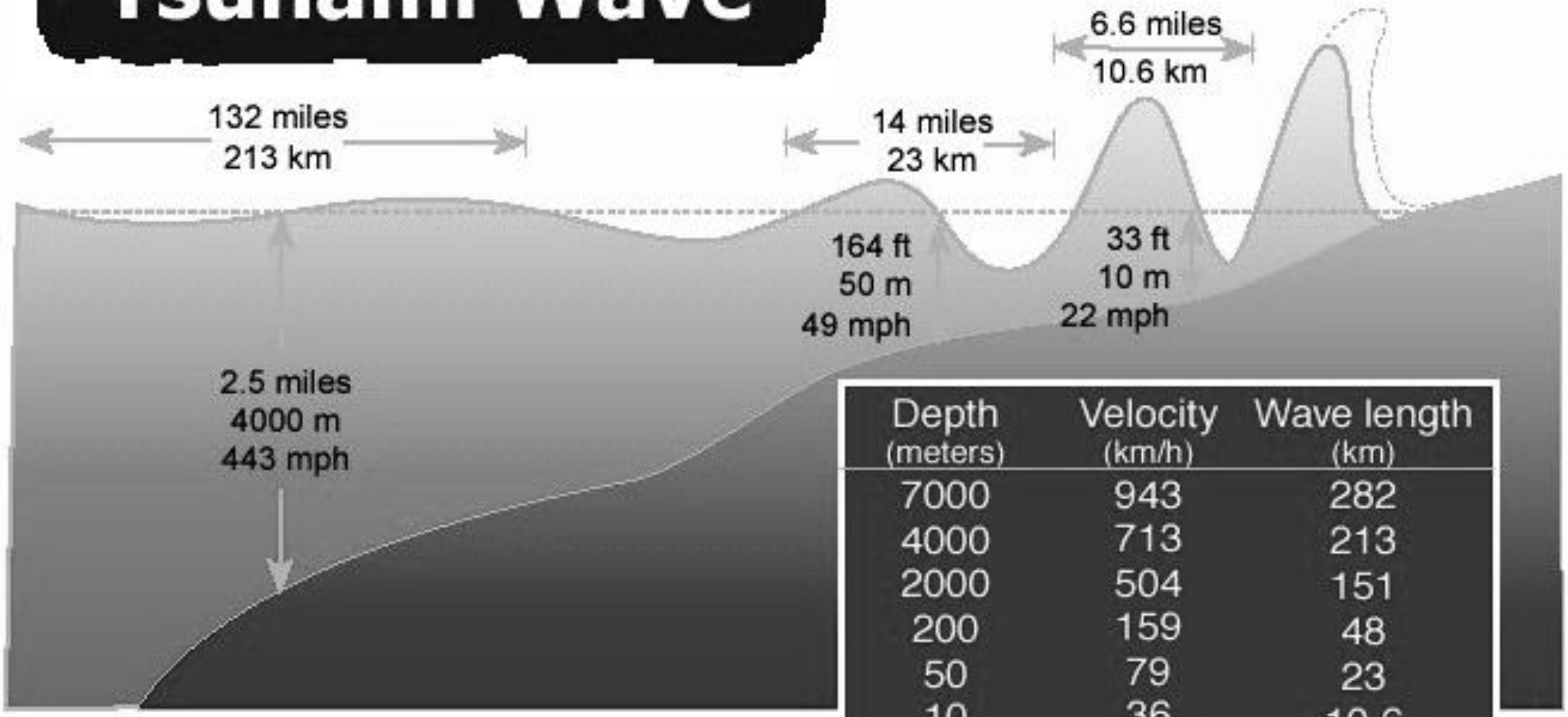
- Seafloor quickly changes shape
- Water is displaced
- Waves are formed as the displaced water mass, which is affected gravity, tries to move back

Tsunami



- Notice how the wave height increases as it approaches the shore.
- Wave heights are typically between 8 to 40 feet (100 ft waves have been recorded).
- Wave heights can be amplified by the coastline.
- The interval between waves can vary from minutes to hours.
- The speed of the waves is proportional to the water depth, and therefore decreases as it approaches the shore.

Tsunami Wave

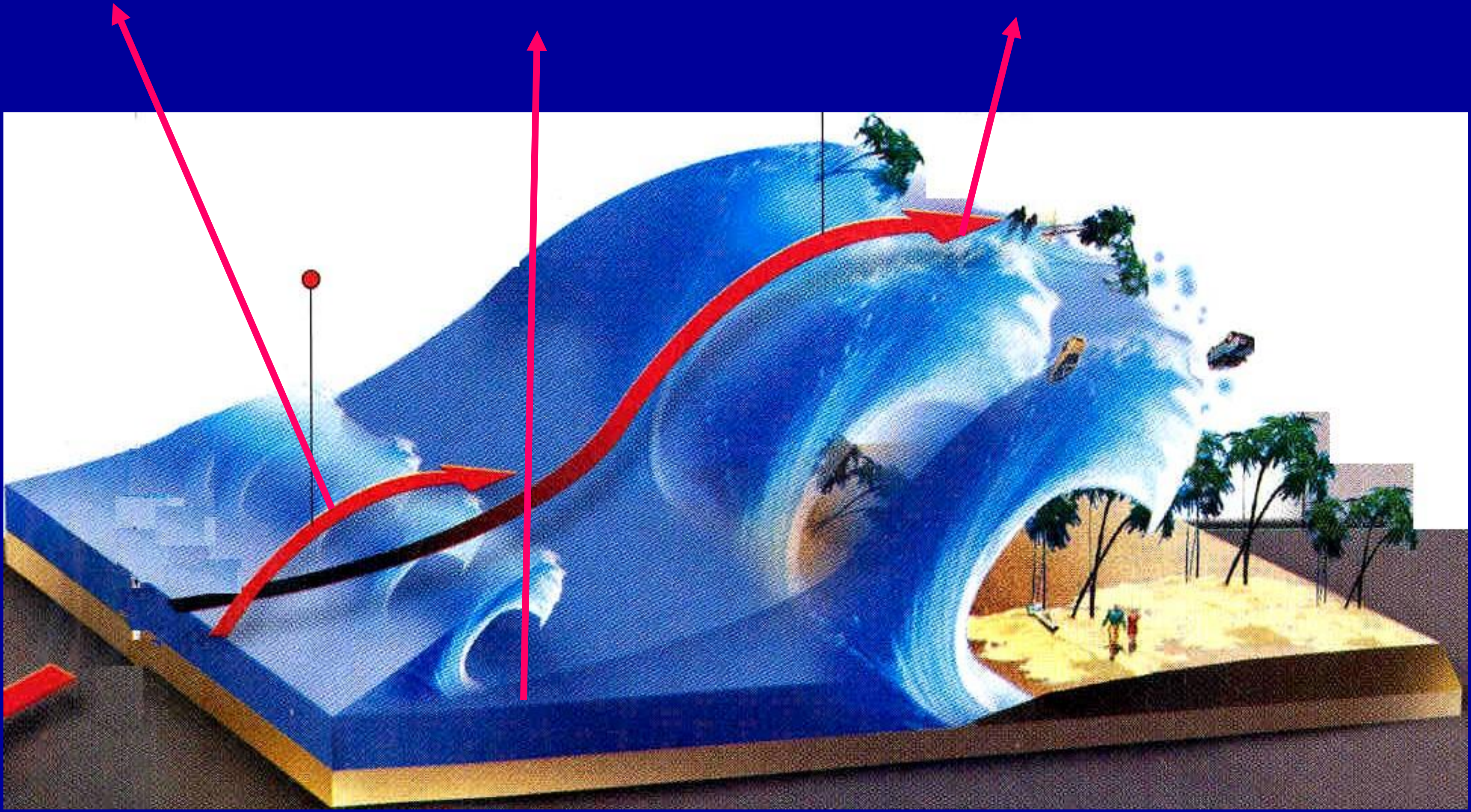


Depth (meters)	Velocity (km/h)	Wave length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

As it enters shallow water, tsunami wave speed slows and its height increases, creating destructive, life-threatening waves.

Depth (miles)	Velocity (mph)	Wavelength (miles)
4.4	586	175
2.5	443	132
1.2	313	94
635 ft	99	30
164 ft	49	14
33 ft	22	6.6

Triggering Mechanism of Tsunamis

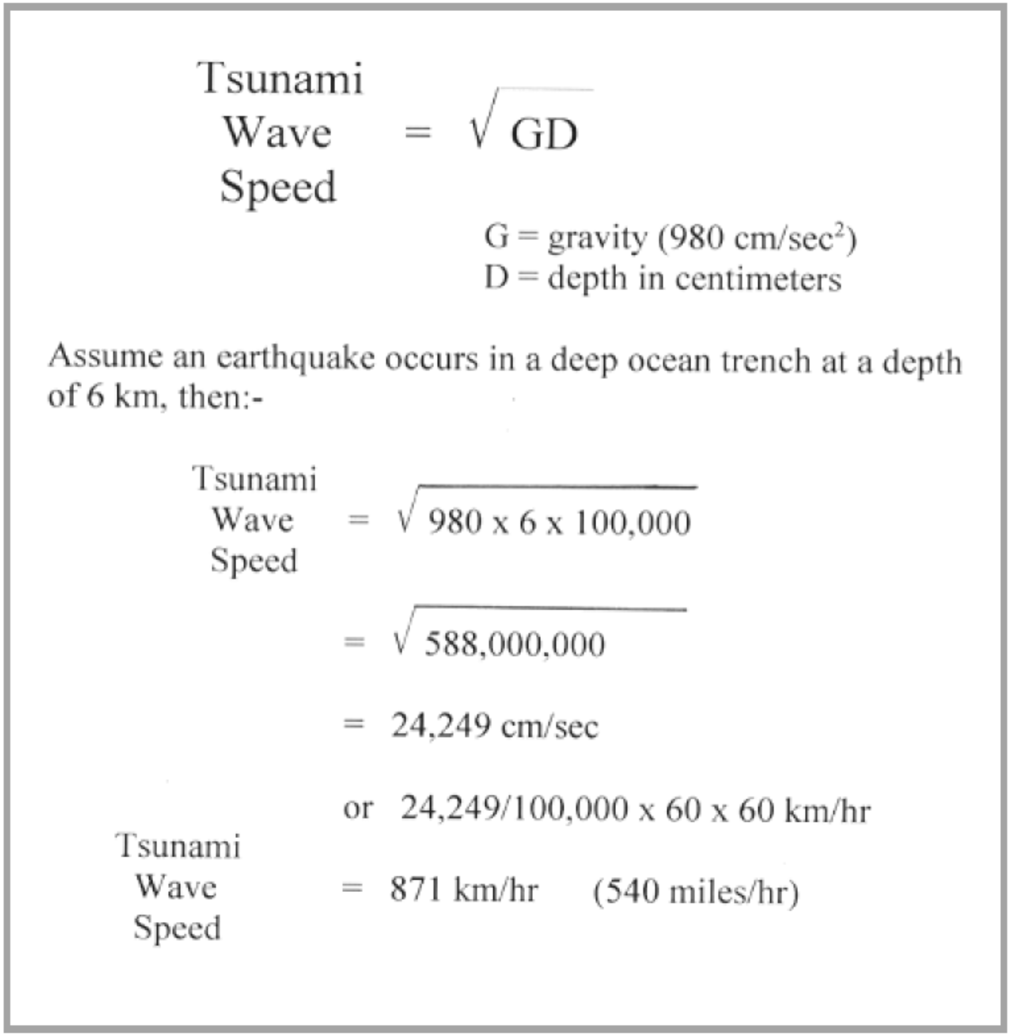


Height - 1m
Speed - 700 km/h

Self Margin

Height - 10m
Speed - 40 km/h

Calculating the Tsunami Wave Speed



$$\text{Tsunami Wave Speed} = \sqrt{GD}$$

G = gravity (980 cm/sec^2)
D = depth in centimeters

Assume an earthquake occurs in a deep ocean trench at a depth of 6 km, then:-

$$\text{Tsunami Wave Speed} = \sqrt{980 \times 6 \times 100{,}000}$$

$$= \sqrt{588{,}000{,}000}$$

$$= 24{,}249 \text{ cm/sec}$$

$$\text{or } 24{,}249/100{,}000 \times 60 \times 60 \text{ km/hr}$$

$$\text{Tsunami Wave Speed} = 871 \text{ km/hr} \quad (540 \text{ miles/hr})$$

EARTHQUAKE BELT

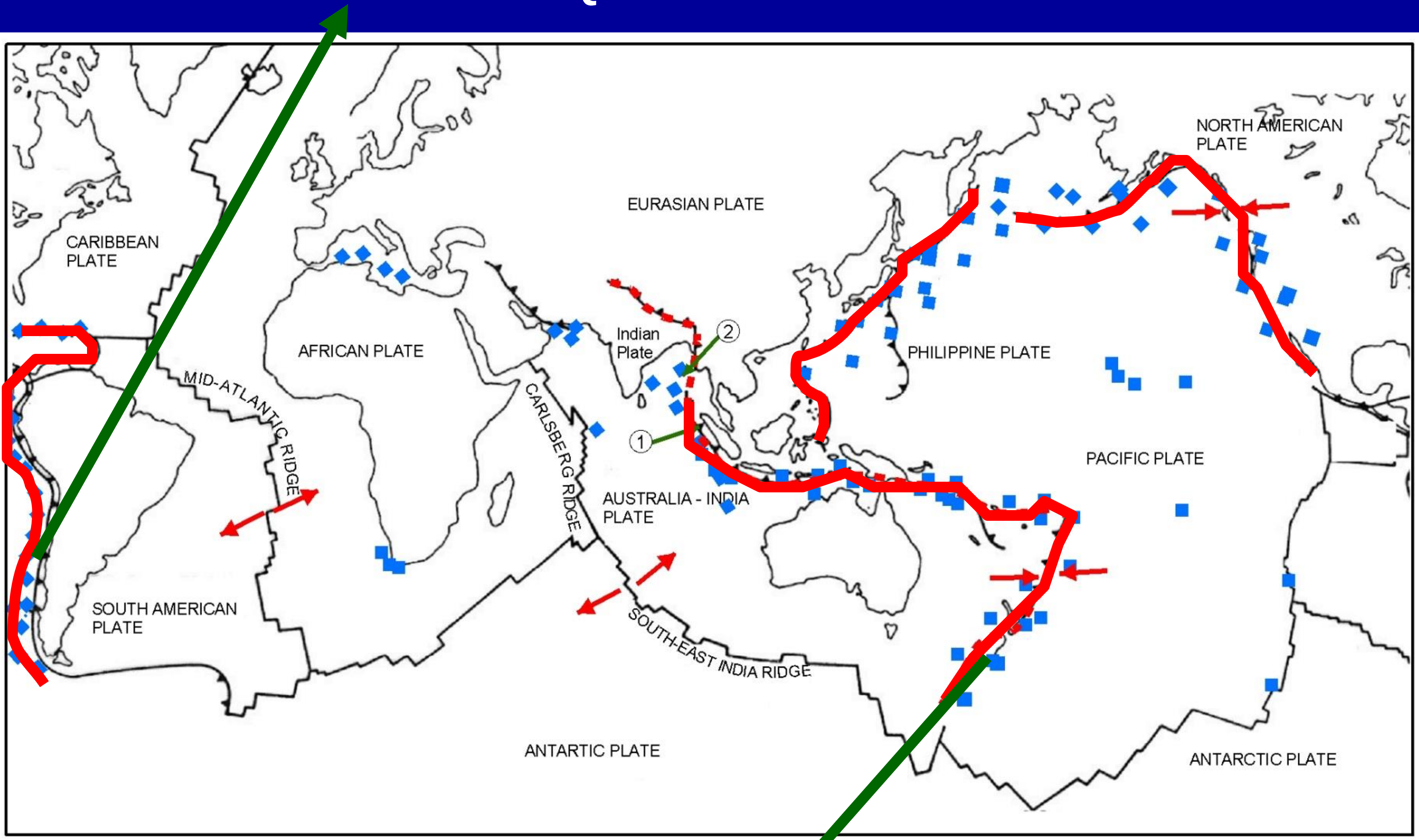


Fig.1 PRESENT POSITIONS OF CONTINENTS - PLATE BOUNDARIES - MAJOR TSUNAMIS EVENTS

Divergent Plate Boundaries

Convergent Plate Boundaries

Indo-Burma-Sumatra Subduction Zone

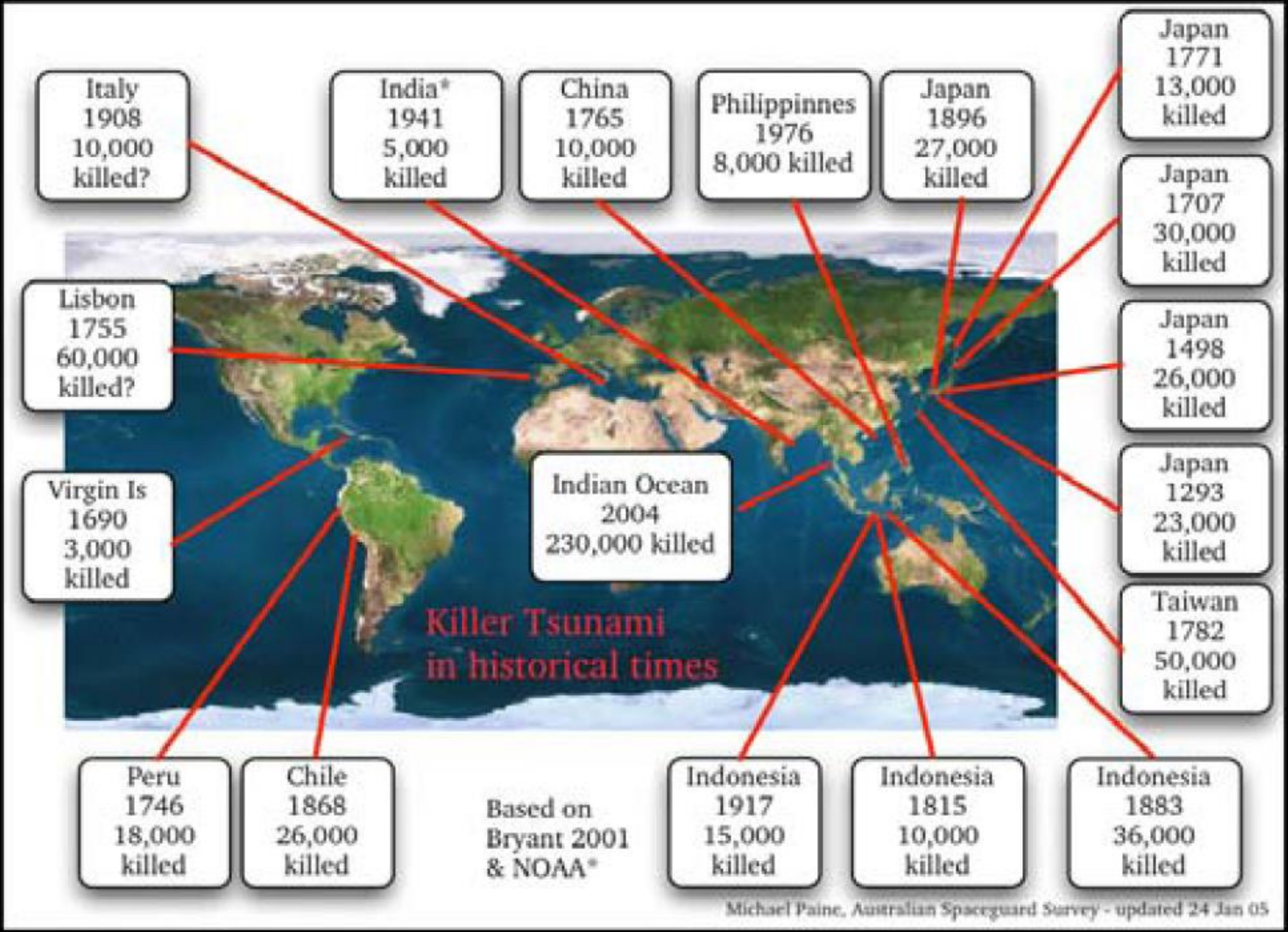
■ ■ Seismically Triggered Tsunamis Belts

① & ② 26th December 2004 Sumatra Earthquake and the Triggered Earthquakes in Andaman

TSUNAMIS PROVINCES

PAST TSUNAMIS OF SUMATRA REGION

- **10, December 1797**
- **24, November 1833**
- **05, January 1843**
- **06, February 1861**
- **02, June 1994**



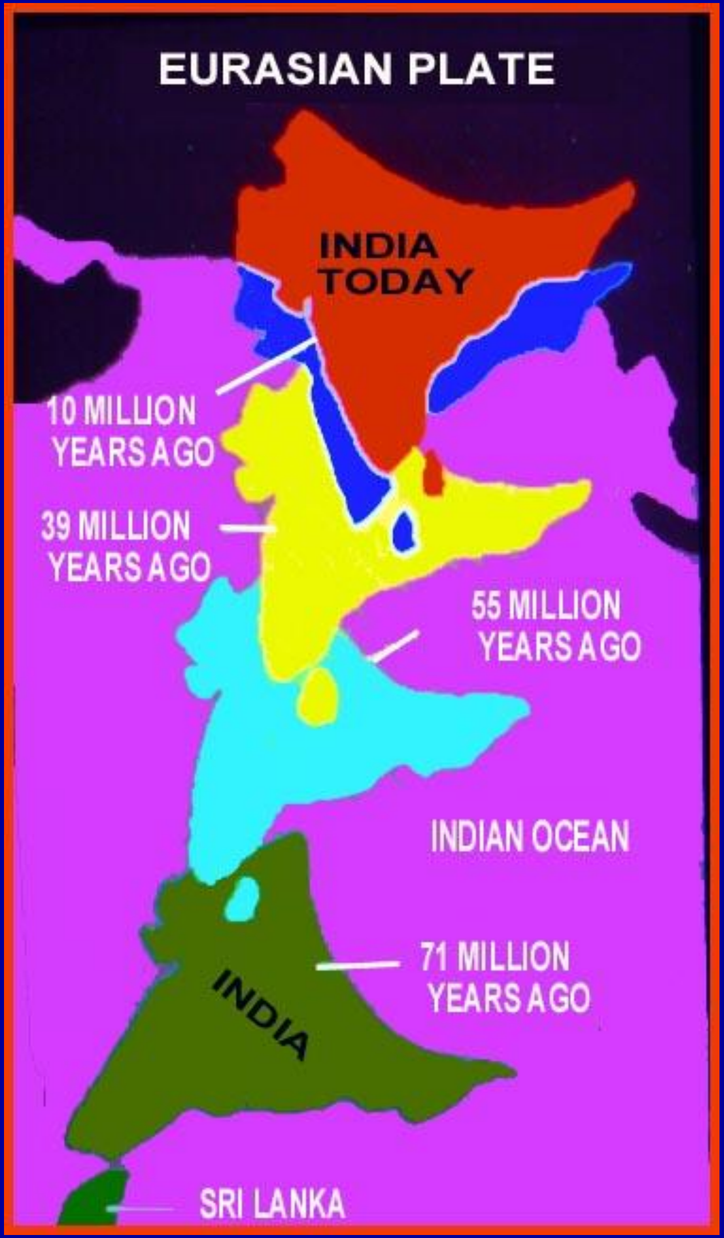
Based on Bryant 2001 & NOAA*

Michael Paine, Australian Spaceguard Survey - updated 24 Jan 05

TSUNAMIS OF

26 DECEMBER 2004

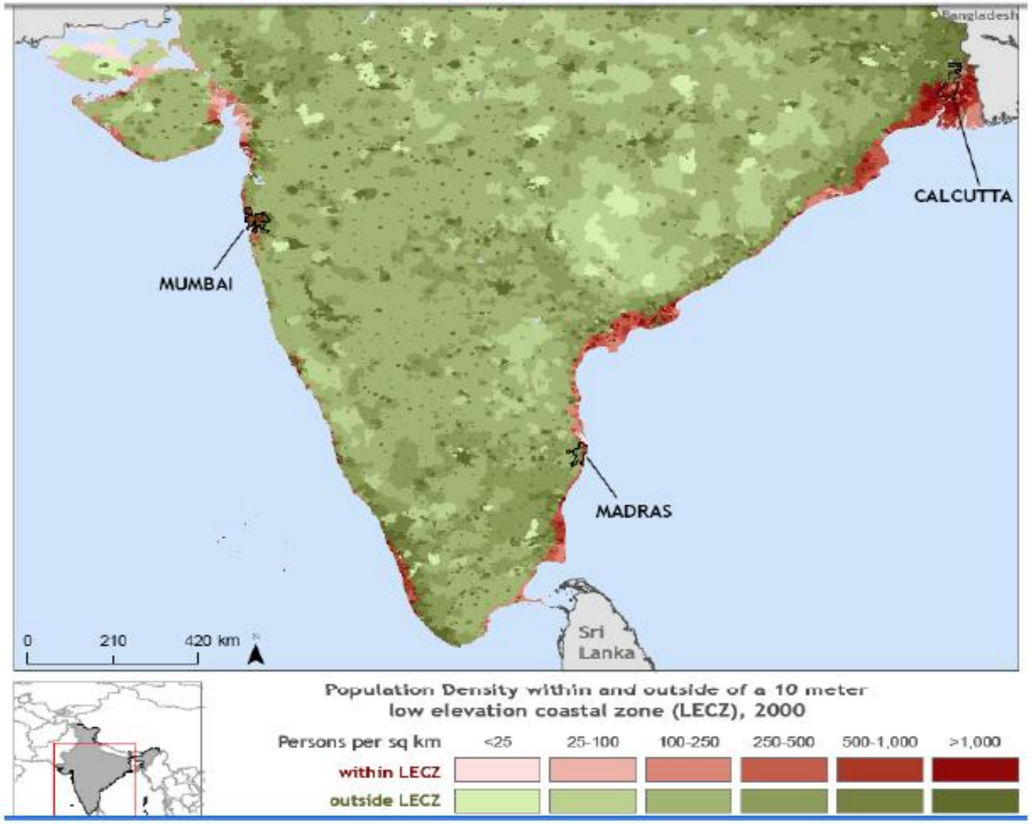
DRIFTING OF INDIAN SUBCONTINENT



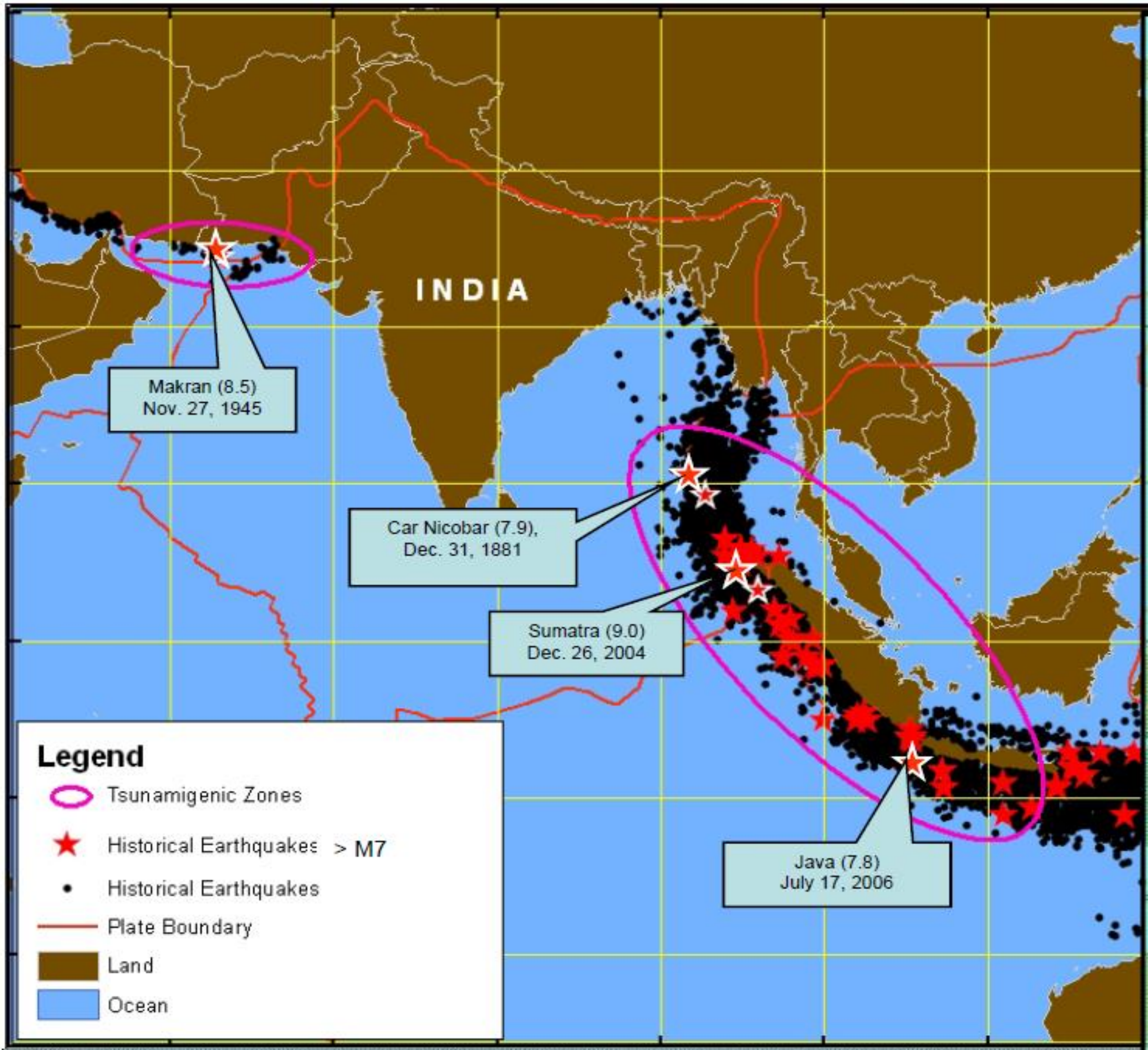
Vulnerability of the Indian Ocean Coastline

- More than 50 Nations around
- Many are Developing Countries
- More than1.5 Billion Population
- More than 66,500 km coastline

- 26 % of Indian Population live within 100 Km from the shoreline
- Most of the coastal areas are low lying and vulnerable to oceanogenic disasters such as Tsunamis, Storm Surges, Sea-level rise
- Dec 26, 2004 Tsunami resulted in a loss of 18, 045 deaths and 6,47,599 persons displaced



Risk Assessment - Historical Earthquakes & Tsunamis



Tsunamis are primarily caused due to large undersea Earthquakes.

For a tsunami to hit Indian coast, it is necessary that a tsunamigenic earthquake occurs and its magnitude should be larger than M 7. Possible locations of such events are enclosed in ellipse

Earthquakes with Slow Rupture Velocities are most efficient Tsunami Generators

75% of earthquake energy is released in the circum-Pacific belt – 900 Tsunamis in 20th Century

20% in the Alpine-Himalayan belt – 6 Tsunamis in 20th Century

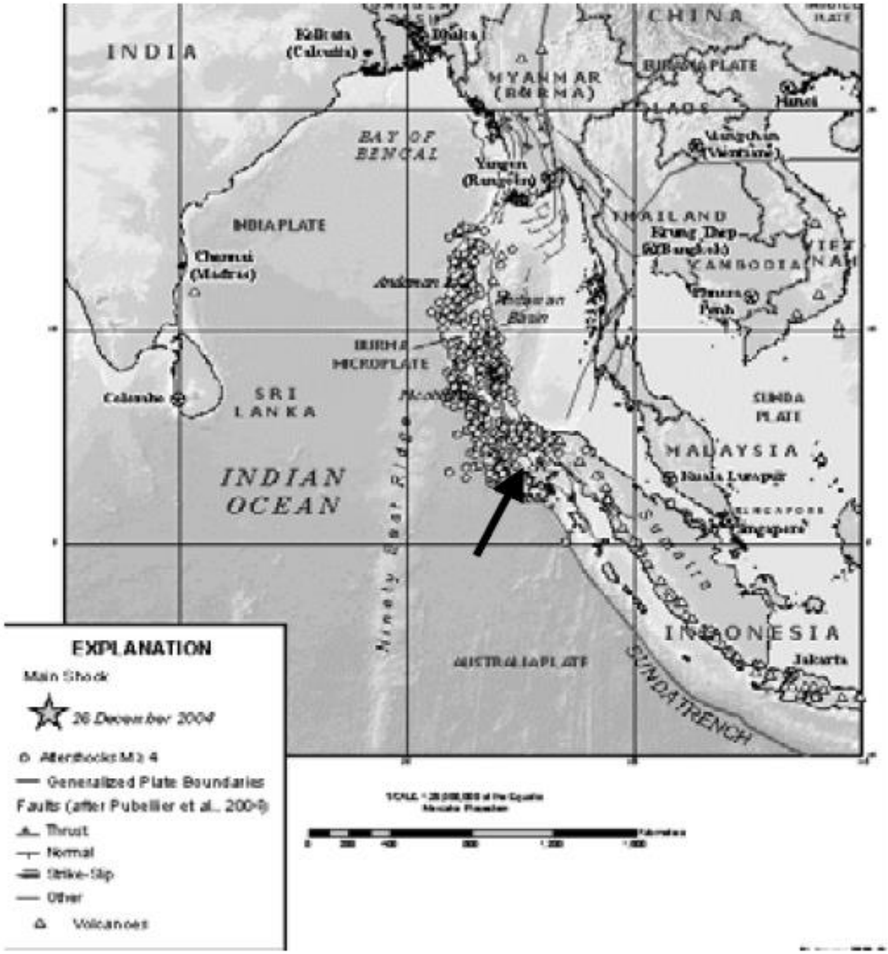
Historical Tsunami in India

12 Apr, 1762 (BoB EQ) – 1.8 M
31 Dec, 1881 (Car Nicobar EQ)
27 Aug, 1883 (Krakatoa) – 2 M
26 Jun, 1941 (Andaman EQ)
27 Nov, 1945 (Makran EQ) – 12 M
26 Dec, 2004 (Sumatra EQ)

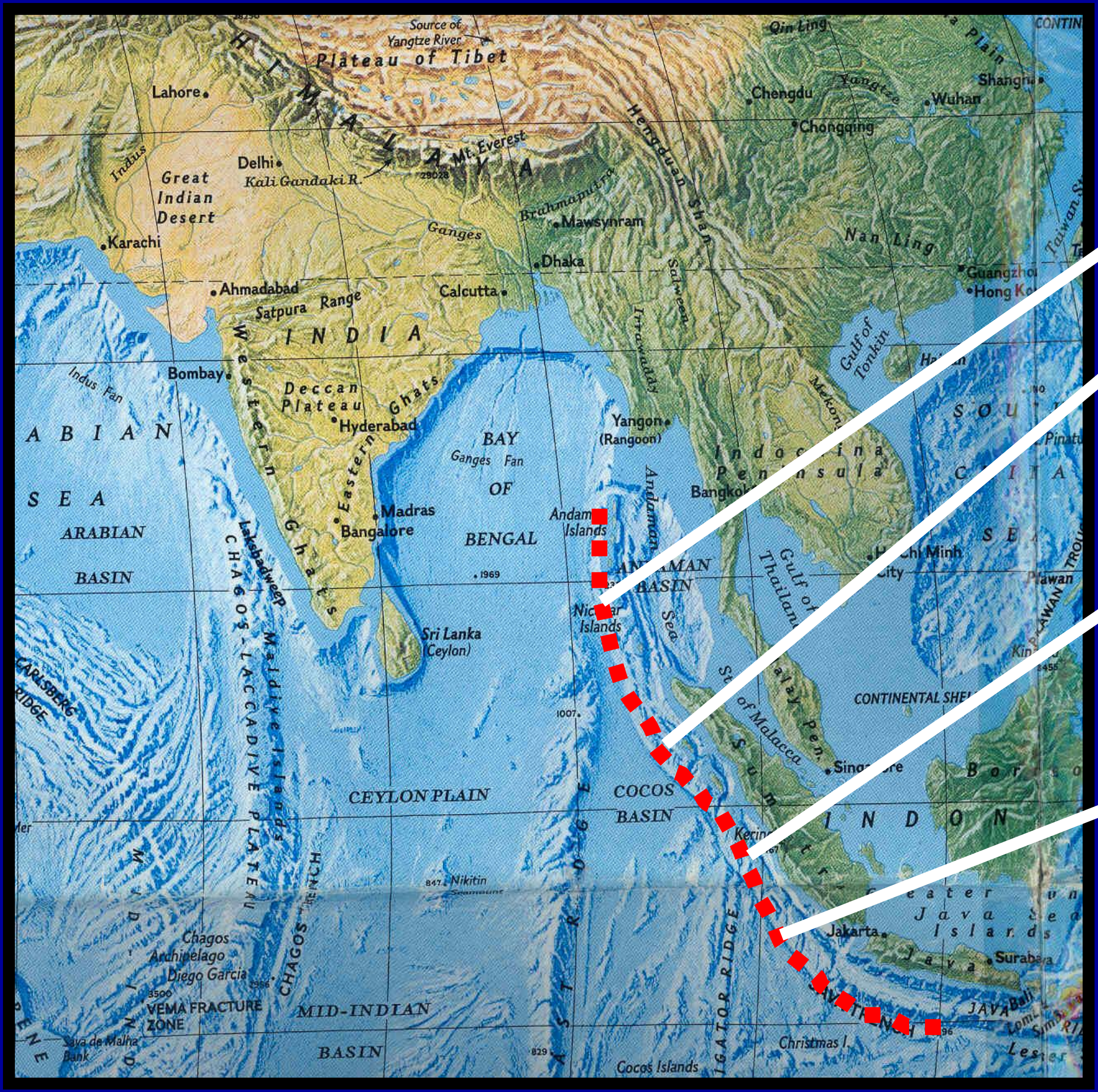
Landslides, Volcanoes & Meteor Impacts can also generate Tsunamis


Source of Yangtze River
Plateau of Tibet
Qin Ling
HIMALAYA
Lahore
Chengdu
Yangtze
Wuhan
Shanghai
Chongqing
Mt. Everest
Hengduan Shan
Delhi
Kali Gandaki R.
Indus
Great Indian Desert
Brahmaputra
Mawsynram
Ganges
Karachi
Dhaka
Nan Ling
Guangzhou
Hong Kong
Ahmadabad
Calcutta
Satpura Range
Salween
Irrawaddy
INDIA
Western Ghats
Gulf of Tonkin
Hainan
Bombay
Indus Fan
Deccan Plateau
Eastern Ghats
Mekong
Hyderabad
Yangon (Rangoon)
SOUTH CHINA SEA
ARABIAN SEA
BAY OF BENGAL
Ganges Fan
Indochina Peninsula
Bangkok
Madras
Bangalore
Andaman Islands
ANDAMAN BASIN
Gulf of Thailand
Ho Chi Minh City
Palawan
ARABIAN BASIN
Lakshadweep
CHAGOS-LACCADIVE PLATEAU
Maldive Islands
Nicobar Islands
Sri Lanka (Ceylon)
Str of Malacca
Malay Pen.
Kinabalu
CARLSBERG RIDGE
CONTINENTAL SHELF
Singapore
Sumatra
Borneo
CEYLON PLAIN
COCOS BASIN
INDONESIA
Kerinci
Nikitin Seamount
Greater Sunda Islands
Java Sea
Jakarta
Java
Surabaya
Chagos Archipelago
Diego Garcia
CHAGOS TRENCH
VEMA FRACTURE ZONE
MID-INDIAN BASIN
NINETYEAST RIDGE
INVESTIGATOR RIDGE
JAVA TRENCH
Bali
Lombok
Christmas I.
Cocos Islands
Saya de Malha Bank

Sumatran Earthquake and Tsunami December 26th, 2004



- Megathrust along subduction zone between Australian plate and Burma and Sunda microplates.
- 1200 km long displacement zone, most of which occurred 500 km N.W. of epicenter.
- Maximum of 20 m displacement
- Magnitude 9.0
- Fourth largest earthquake since 1900 A.D. and largest since 1964 Alaska earthquake.
- Equivalent to 475 megatons of TNT (23,000 Nagasaki A-bomb).
- Triggered a massive tsunami

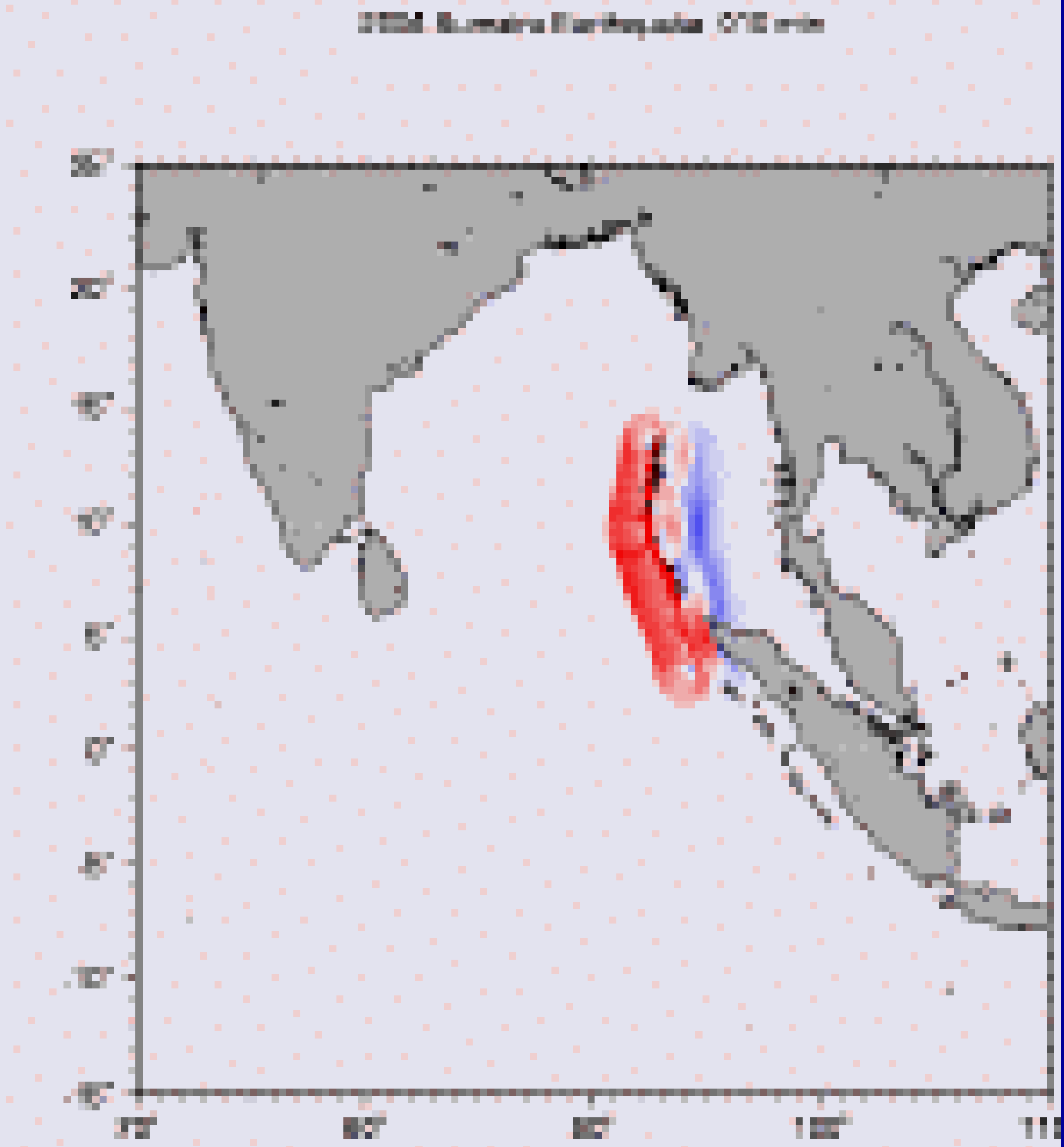


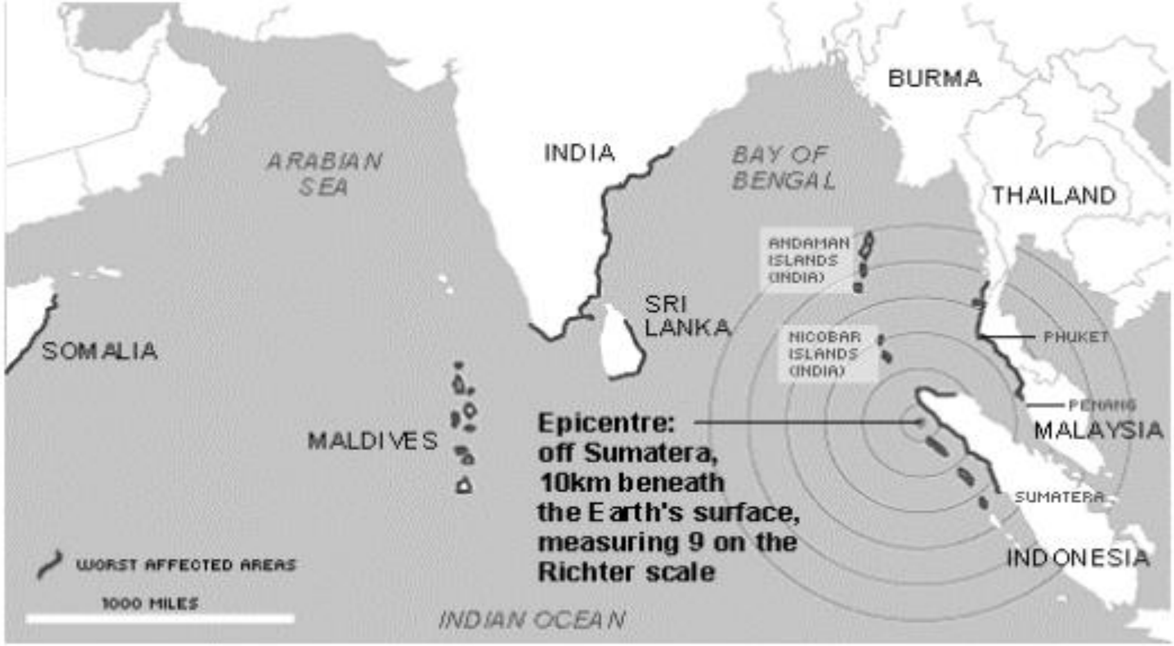
Length of subduction – 1200 km

Width of rupture – 100 km

Depth of subduction – 15mts

Energy released – 4.75 Lakh Kiloton = 23,000 Hiroshima bombs


2004 Sumatra Earthquake 0:10 min
25°
20°
15°
10°
5°
0°
-5°
-10°
-15°
70°
80°
90°
100°
11



**Epicentre:
off Sumatera,
10km beneath
the Earth's surface,
measuring 9 on the
Richter scale**

Tsunami traveled across entire Indian Ocean, affecting Indonesia, Malaysia, Thailand, India, Sri Lanka, Maldives, Somalia, Madagascar and Tanzania. Maximum wave height was about 25 m (80 ft).

<u>Travel Times</u>

India ~ 2 hours

E. Africa ~ 7 hours

TSUNAMIS IN THAILAND

BEACH-FRONT RESTAURANT, THAILAND

TSUNAMIS IN INDONESIA

BANDA BEACH

BANDA_ACEH_NORTHERNSHORE

June 23 2004

Dec 28 2004

INDONESIA

January 13 2003

December 29 2004

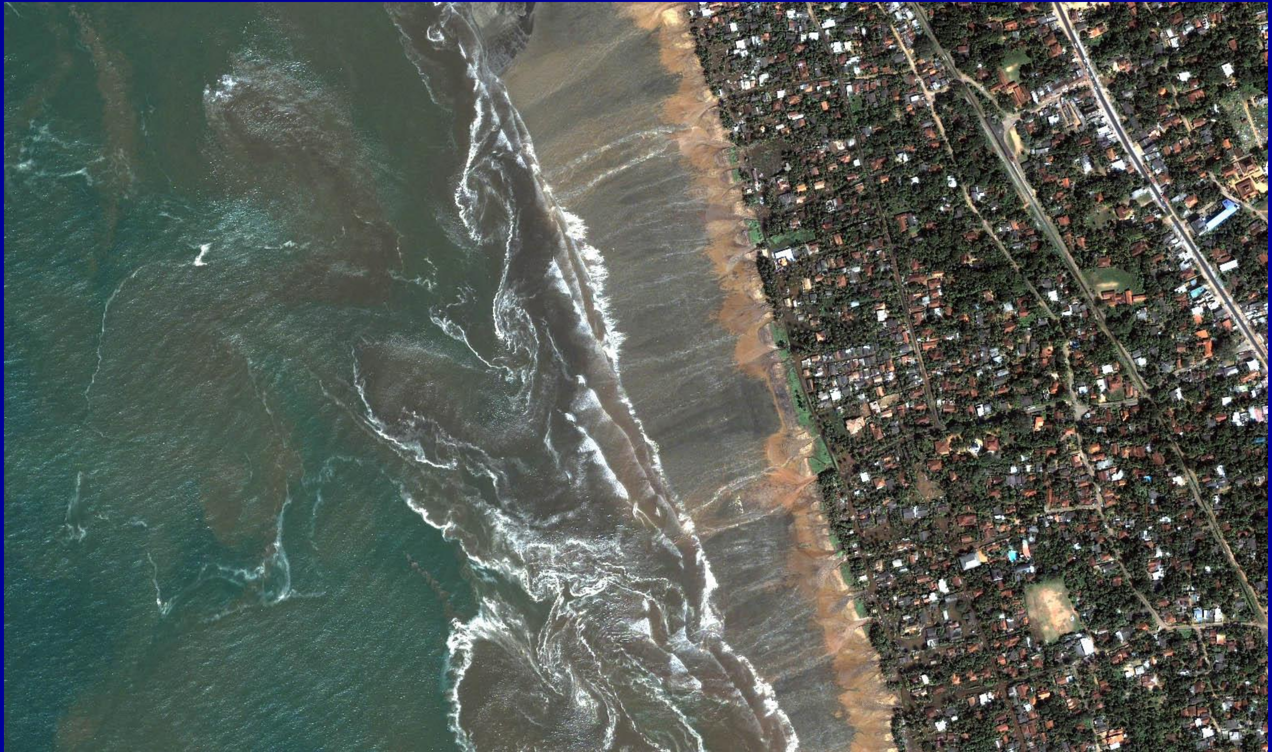
TSUNAMIS IN MALAYSIA

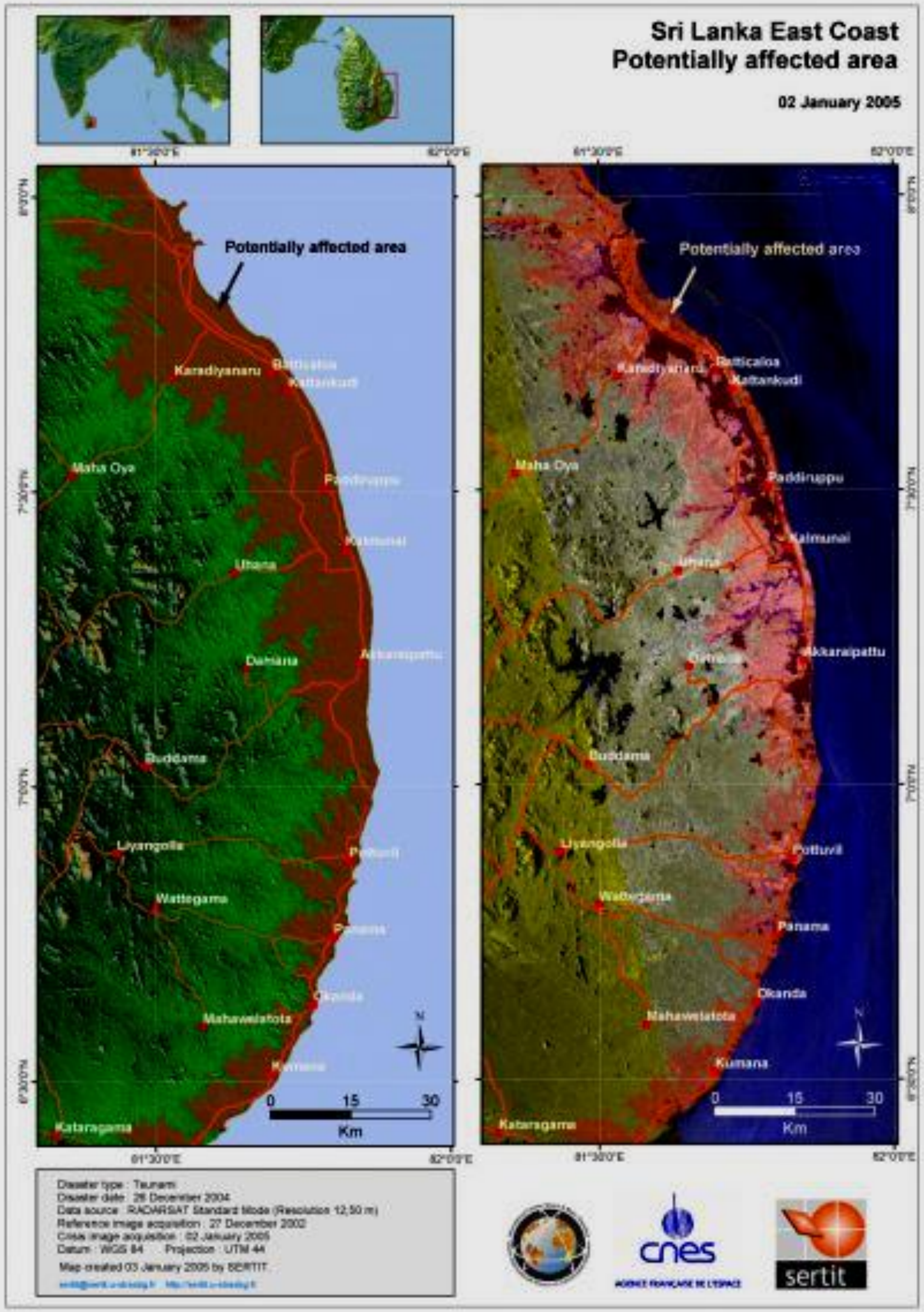

AP PHOTO/ANDY WONG

TSUNAMIS IN SRILANKA

KALUTHARA SEA SHORE OF SOUTH WEST SRILANKA ISLAND

(TSUNAMI ATTACK)





Sri Lanka East Coast Potentially affected area

02 January 2005

Disaster type : Tsunami
Disaster date : 26 December 2004
Data source : RADARSAT Standard Mode (Resolution 12,50 m)
Reference image acquisition : 27 December 2002
Crisis image acquisition : 02 January 2005
Datum : WGS 84 Projection : UTM 44

Map created 03 January 2005 by SERTIT

[illegible]

TSUNAMIS IN INDIA

CHENNAI MARINA BEACH

CHENNAI MARINA BEACH

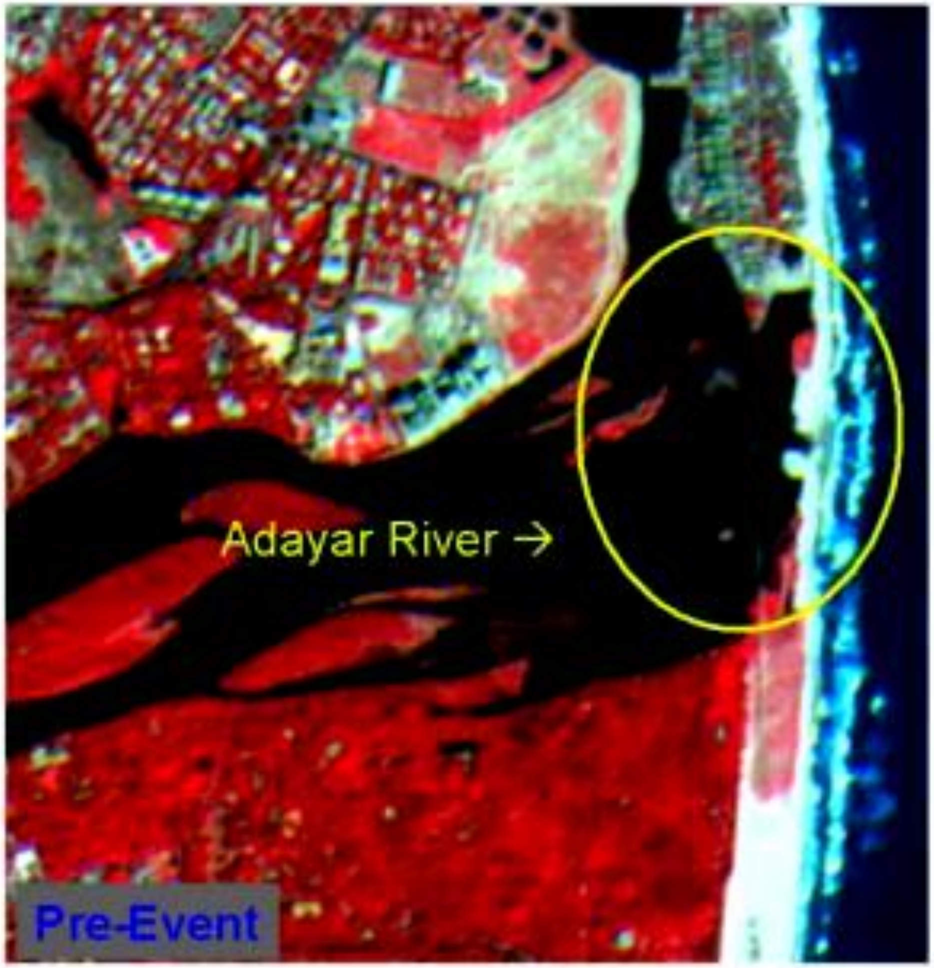
CHENNAI MARINA BEACH

TSUNAMI AFFECTED ENNORE – FISHING HARBOR

Tsunami - 2004

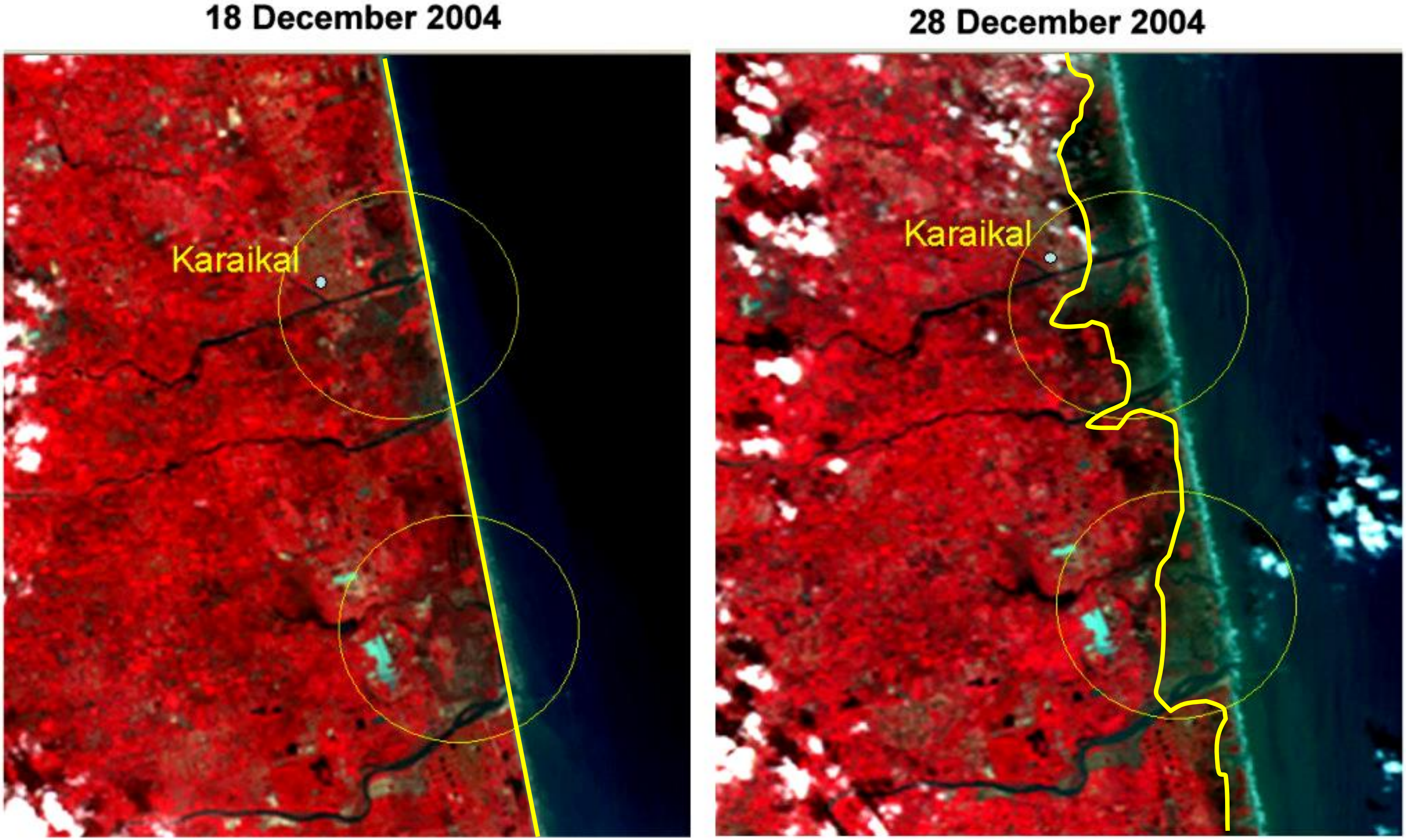
Part of Chennai City

IRS-P6 L4 MX Image of 12-Jan-04



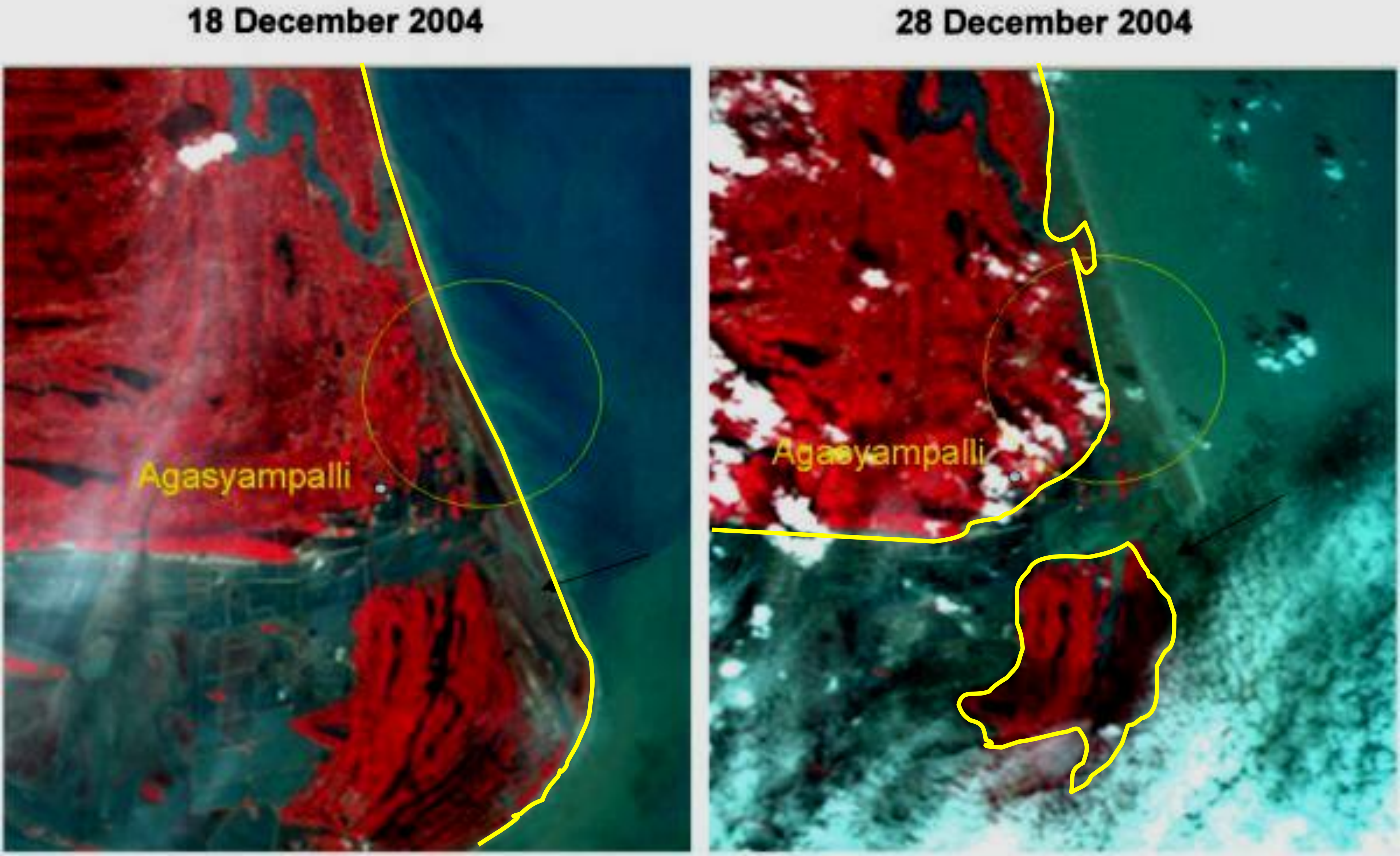
IRS-P6 L4 MX Image of 27-Dec-04

IRS P6 AWIFS Data



Nagapattinam

IRS P6 AWIFS Data



18 December 2004

28 December 2004

VEDARANNIYAM

Method of Splitting Tsunami (MOST) Model

Tsunami modeling using MOST proceeds in three distinct stages:

A Deformation Phase generates the initial conditions for a tsunami by simulating ocean floor changes due to a seismic event.

A Propagation Phase propagates the generated tsunami across deep ocean using Nonlinear Shallow Water (NSW) wave equations.

An Inundation Phase simulates the shallow ocean behavior of a tsunami by extending the NSW calculations using a multi-grid “run-up” algorithm to predict coastal flooding and inundation.

MOST simulations using all three phases require the following sets of input data:

- **The amount and distribution of the sea-floor dislocation, induced by a seismic event.**

- **Gridded bathymetric data information for the open ocean propagation.**

- **A set of gridded Digital Elevation Models (DEM) containing bahtymetry and topography for use during the inundation phase. The set consists of one DEM that contains bathymetric and topographical information, and two DEMs that contain bathymetrical information and optional topographical information.**

Table 3 MOST Digital Elevation Model Grids Data Requirements

MOST Simulation Phase	Detailed Bathymetry	Detailed Topography
Deformation	Required	Not Required
Propagation	Required	Not Required
Inundation: Grid A (Outer)	Required	Optional unless run-up enabled
Grid B (Intermediate)	Required	Optional unless run-up enabled
Grid C (Inner)	Required	Required

Table 4 MOST Digital Elevation Model Grids Spatial Resolution

MOST Stage	Recommended Resolution	Lowest Required Resolution*
Deformation/Propagation	1 arcminute (~1800 m)	4 arcminutes (~7300 m)
Inundation: Grid A (Outer)	36 arcseconds (~1080 m)	2 arcminutes (~3600 m)
Grid B (Intermediate)	6 arcseconds (~180 m)	18 arcseconds (~500 m)
Grid C (Inner)	≤ 1 arcsecond (≤ 30 m)	2 arcseconds (60 m)

*Note: Equivalent meter value on the Equator.

Table 6 Some Recommended Sources of DEM Data

Coverage	Sources	Type	Links
Global	ETOPO2	bathymetry, topography	http://www.ngdc.noaa.gov/mgg/global/global.html
	GEBCO	bathymetry, topography	http://www.ngdc.noaa.gov/mgg/gebco/gebco.html
U.S. and its territories	NOAA	bathymetry, topography, shoreline, datum	http://www.ngdc.noaa.gov/ http://www.nos.noaa.gov/
	USGS	topography, photography, bathymetry	http://seamless.usgs.gov/
	USACE	bathymetry, shoreline	http://www.usace.army.mil/
	State agencies, universities	various	various
Local region	Local Agencies	various	various

Seismic Inputs

Significant changes to the ocean floor along a fault plane are characterized by a strike, a dip, a slip or rake angle of the fault plane; the ocean floor slip magnitude (dislocation) along the fault plane trace; and the epicenter of the seismic event responsible for the undersea deformation.

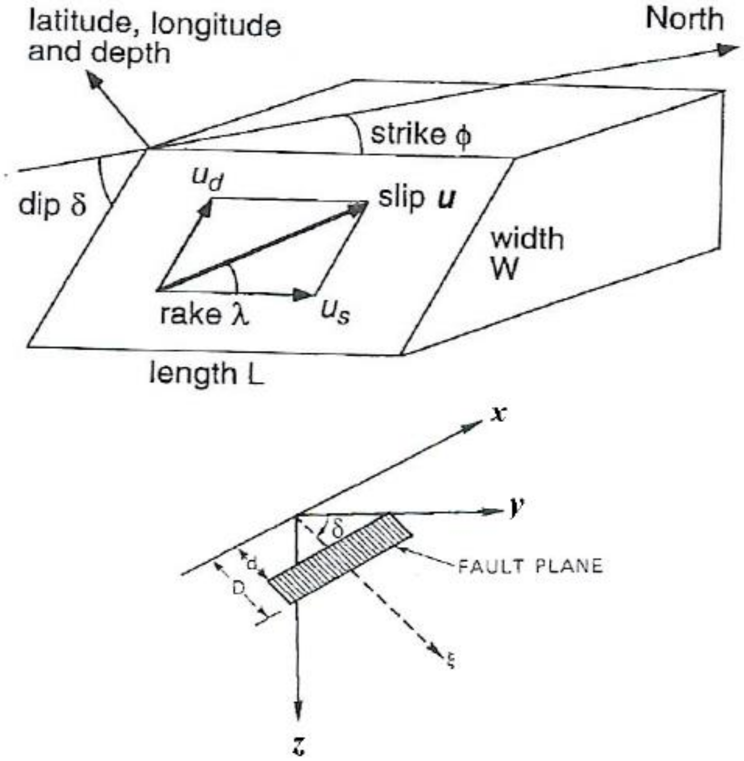


Figure 3: Earthquake Fault Parameters and Geometry System

Sea floor dislocation due to a rupture along a fault is expressed in terms of a deformation rectangular area—a region of ocean bottom bisected by the fault trace, with an orientation determined by the strike angle.

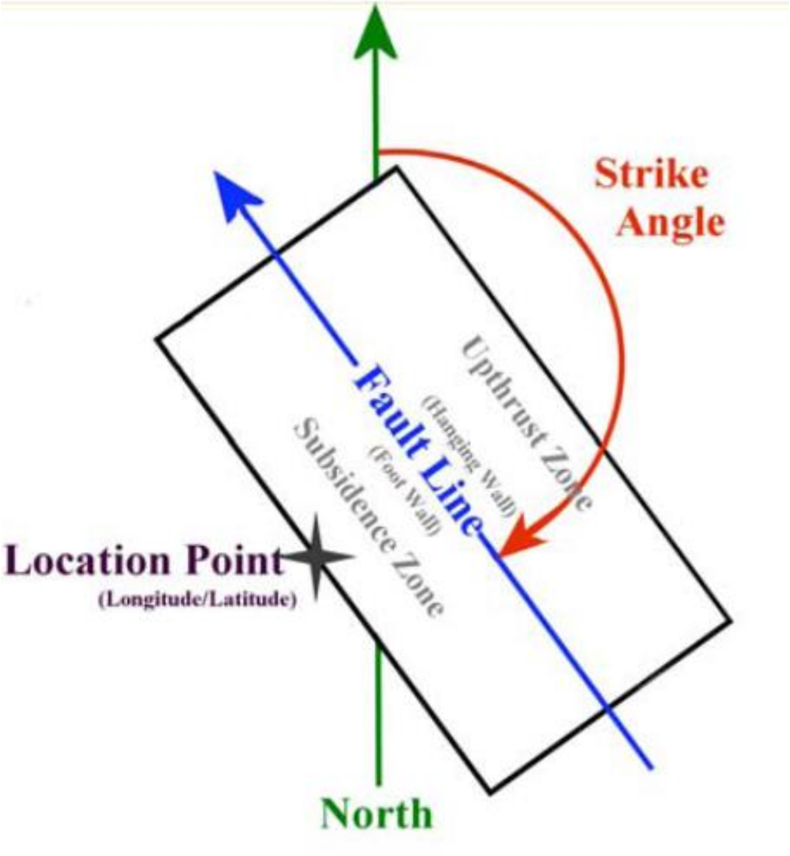


Figure 4: Deformation Rectangle

The fault line projects through the center of the deformation rectangle and divides the rectangle into a region of upthrust on the hanging wall side of the fault, and a region of subsidence on the foot wall side of the fault. The center of the deformation rectangle side parallel to the foot wall (on the subsidence side of the rectangle) is its location point or location reference—the point referred to by the longitude and latitude of the rectangle.

Using Multiple Deformation Rectangles

A given deformation rectangle should closely conform to a particular disruption occurring on the ocean floor. To model a real-world seismic fault, you need to decompose the rectangle into multiple deformation rectangles that are as contiguous and non-overlapping as possible.

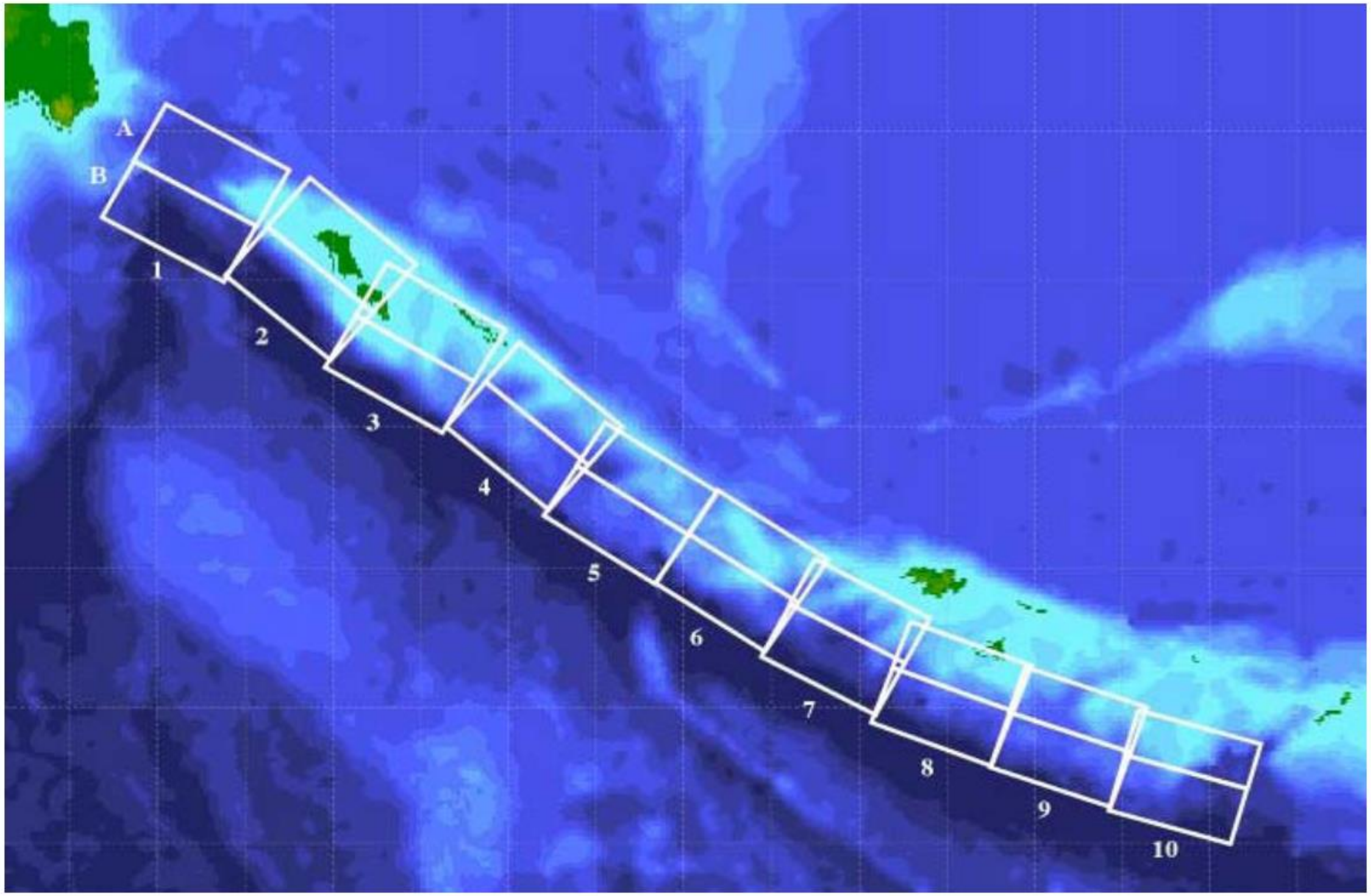


Figure 5: Fault Decomposed to Reformation Rectangles

Seismic Data Inputs to deform

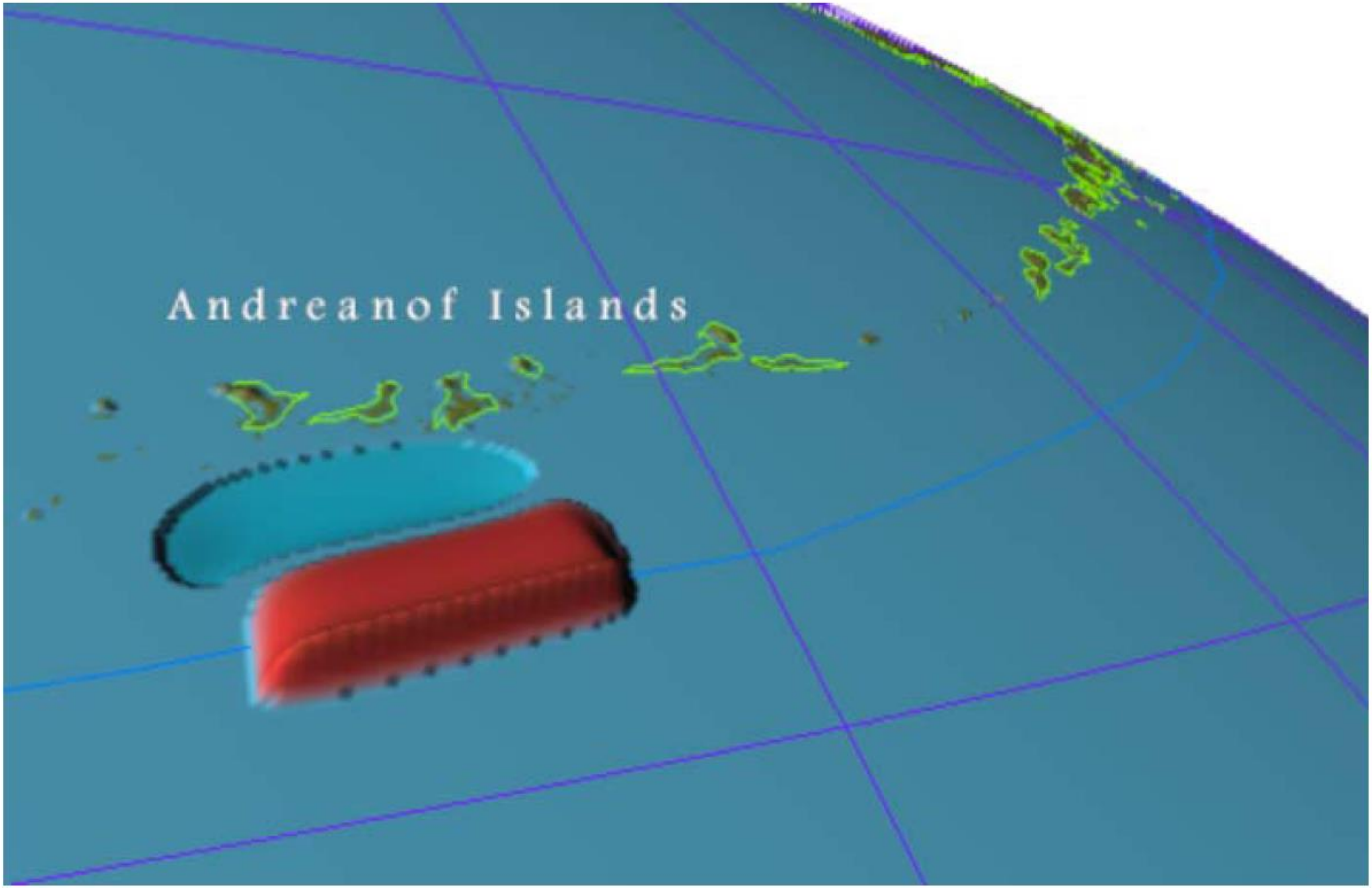
The specification of a deformation rectangle and the size (in terms of nodes on a DEM finite difference grid) of a target sub-grid region on the ocean surface provide the seismic input data to **deform**.

A deformation rectangle is defined using the following parameters:

- latitude of the deformation rectangle
- longitude of deformation rectangle (in East degrees)
- length of deformation rectangle (in km)
- width of deformation rectangle (in km)
- seismic epicenter depth (in km)
- slip magnitude (in m)
- strike angle
- dip angle
- rake angle (also known as the slip angle)

All of these values are supplied to the *`stdin`* of **deform**.

Deformation Phase Outputs



Projection of Deformation Rectangle to Deformation Phase Output Area

Propagation Phase Modeling

The Propagation Phase models the open-ocean evolution of a tsunami using a depth-integrated version of Nonlinear Shallow Water (NSW) wave equations in two spatial and one temporal dimension. The output of a Propagation Phase calculation—the wave's height, and zonal and meridional velocities—is saved for selected time steps and provides the initial and boundary conditions for Inundation Phase.

Ocean Displacement Inputs to Propagation Phase

The ocean displacement inputs to **propagation** are created by **deform**. These inputs define the initial tsunami wave state and provide forcing functions to Propagation Phase calculations.

All Deformation Phase output produced by **deform** and used as input to the Propagation Phase must be calculated using the same DEM data set that was used as input to **propagation**.

Multiple Deformation Phase outputs can be used as inputs to **propagation**. This allows the decomposition of complicated undersea faulting into several deformation rectangles. Ocean surface displacements due to a deformation rectangle are mapped to a subsection (maximum size 500 x 500) of the nodes that make up the DEM finite difference grid

The MOST propagation model uses a numerical dispersion scheme and the non-linear shallow-water wave equations in spherical coordinates, with Coriolis terms (Murty, 1984):

$$h_t + \frac{(uh)_\lambda + (vh\cos\phi)_\phi}{R\cos\phi} = 0$$

$$u_t + \frac{uu_\lambda}{R\cos\phi} + \frac{vu_\phi}{R} + \frac{gh_\lambda}{R\cos\phi} = \frac{gd_\lambda}{R\cos\phi} + fv$$

$$v_t + \frac{uv_\lambda}{R\cos\phi} + \frac{vv_\phi}{R} + \frac{gh_\phi}{R} = \frac{gd_\phi}{R} - fu,$$

where λ is longitude, ϕ is latitude, $h = h(\lambda, \phi, t) + d(\lambda, \phi, t)$, $h(\lambda, \phi, t)$ is the amplitude, $d(\lambda, \phi, t)$ is the undisturbed water depth, $u(\lambda, \phi, t)$, $v(\lambda, \phi, t)$ are the depth-averaged velocities in the longitude and latitude directions, respectively, g is the gravity acceleration, f is the Coriolis parameter ($f = 2\omega\sin\phi$), and R is the Earth radius. In the MOST model, these equations are solved numerically using a splitting method similar to that described by Titov (1997).

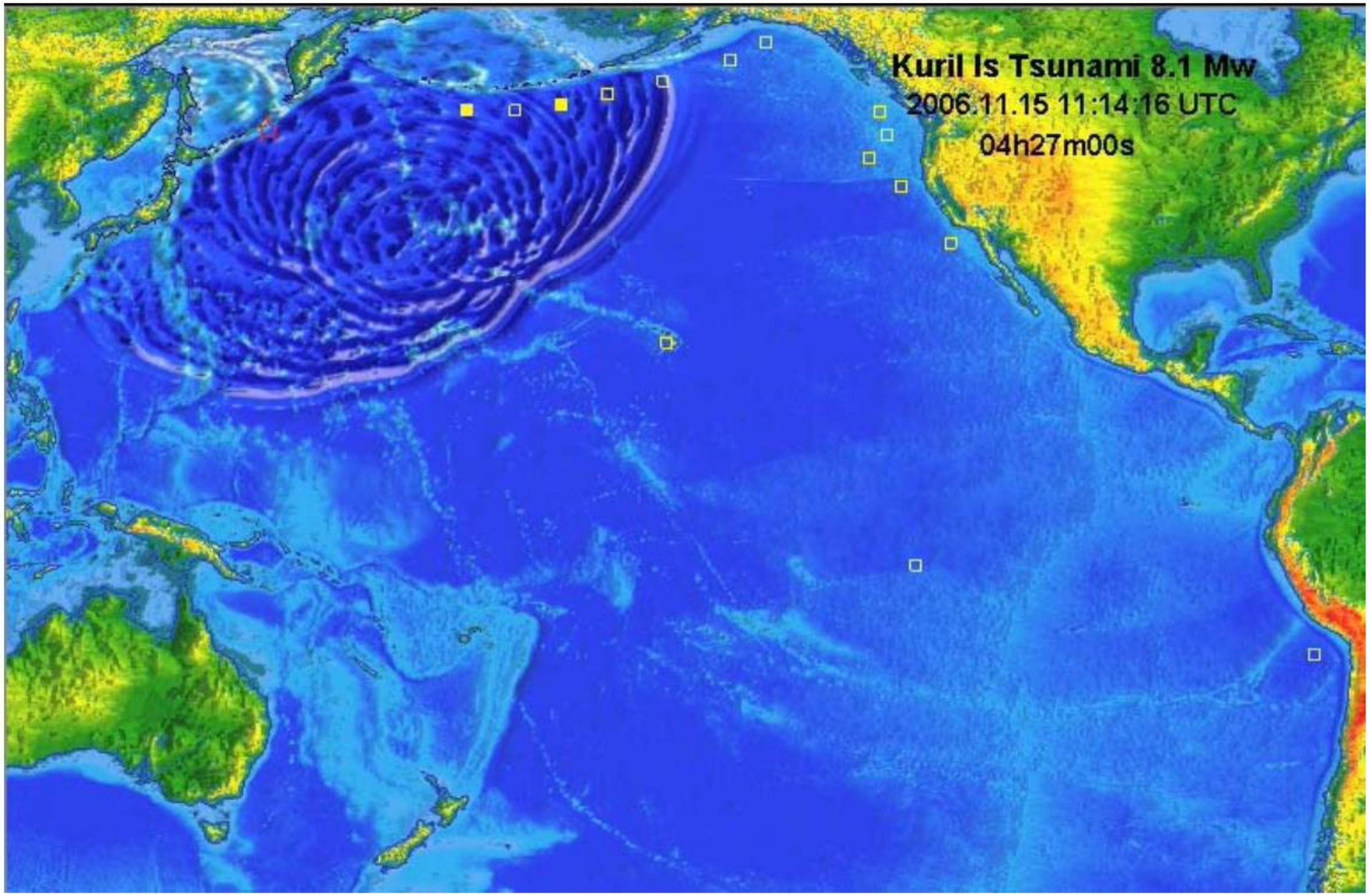
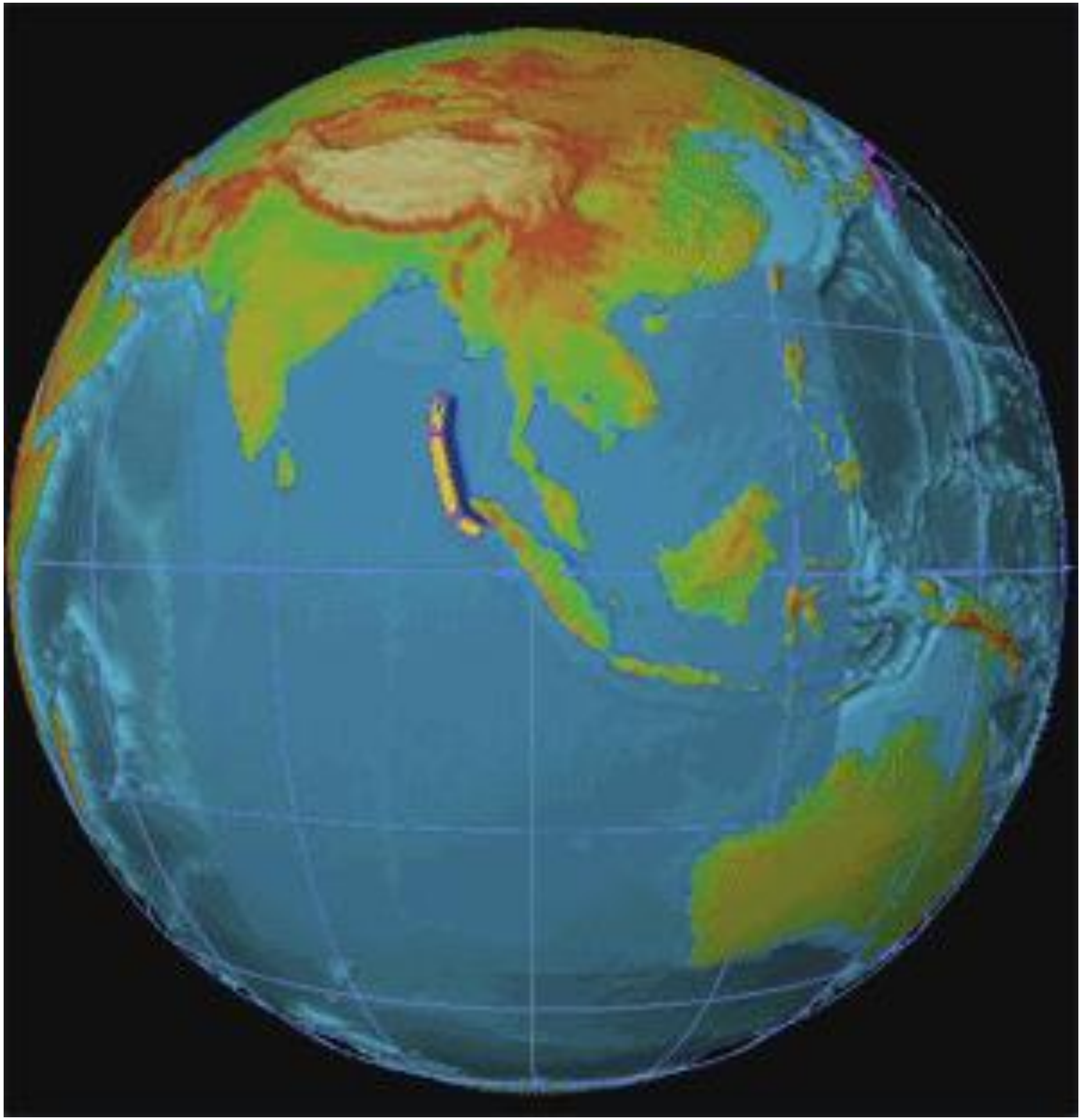
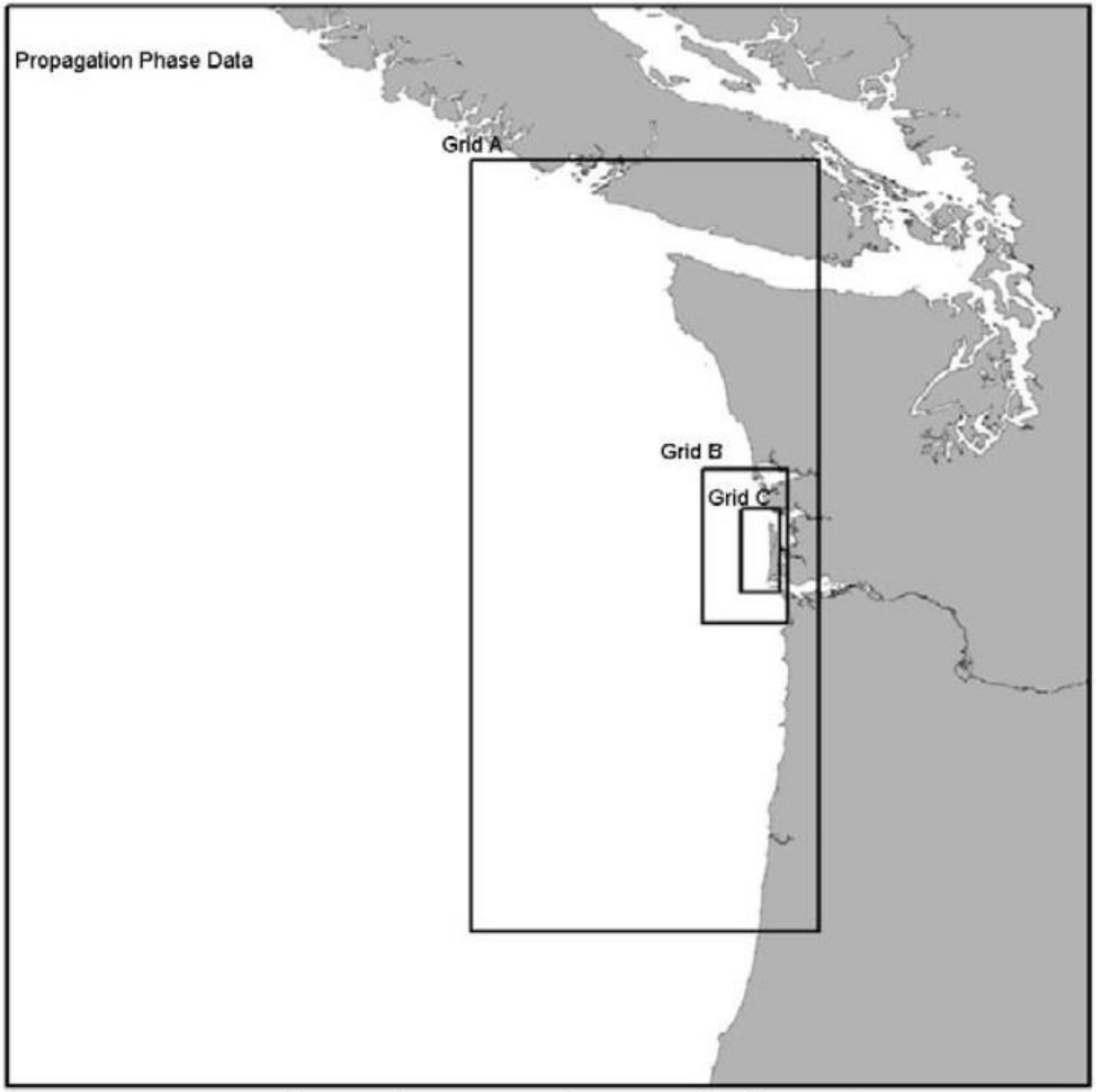


Figure 8: DEM and Tsunami Propagation

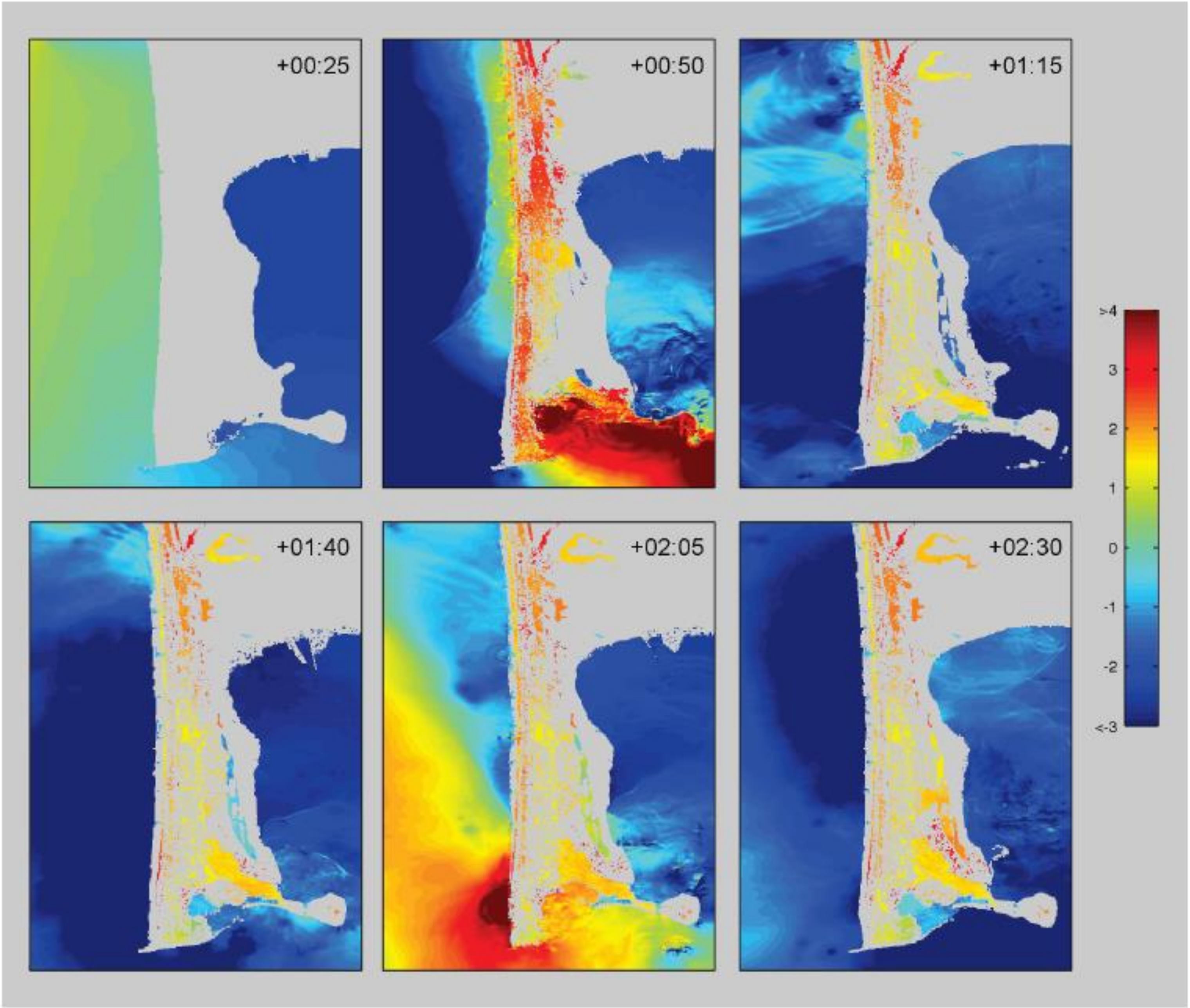
The propagation executable produces three output files, each containing the time-stepped evolution of one of the three components of the wave equations solution. These tsunami components are:

- **Wave height in centimeters.**
- **Meridional velocity in centimeters/second.**
- **Zonal velocity in centimeters/second.**





ure 9: Propagation Phase and Inundation Phase Data Grids


+00:25
+00:50
+01:15
+01:40
+02:05
+02:30
>4
3
2
1
0
-1
-2
<-3

Inundation Phase Modeling

The inundation executable models shoreline tsunami behavior, including onshore run-up. Tsunami behavior is modeled using input from propagation, the depth-integrated NSW wave equations computed on a set of nested DEM grids, and a run-up algorithm to predict onshore flooding.

Inundation Phase output includes wave height, zonal velocity, and meridional velocity for each of the nested NSW calculations. The output is saved for selected time steps

In the present study a detailed attempt was made to bring out

- The interface dynamics between the geosystems and tsunami

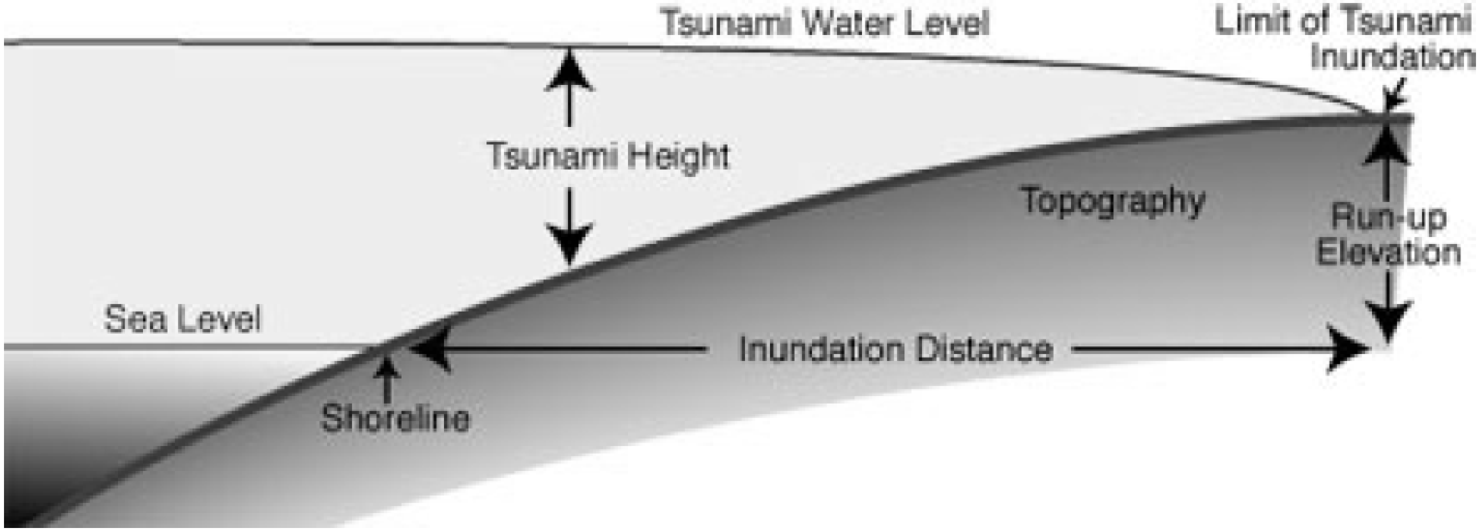
For the same, three types of methodology was adopted

- Visual Modelling – Coastal geometry and Tsunami inundation
- Spatial Modelling – Coastal geomorphology and Inundation
- Linear Modelling – Offshore features and Run up
  - Onshore features and Inundation

Mitigation strategies were carved out.

RUNUP AND INUNDATION MAPPING

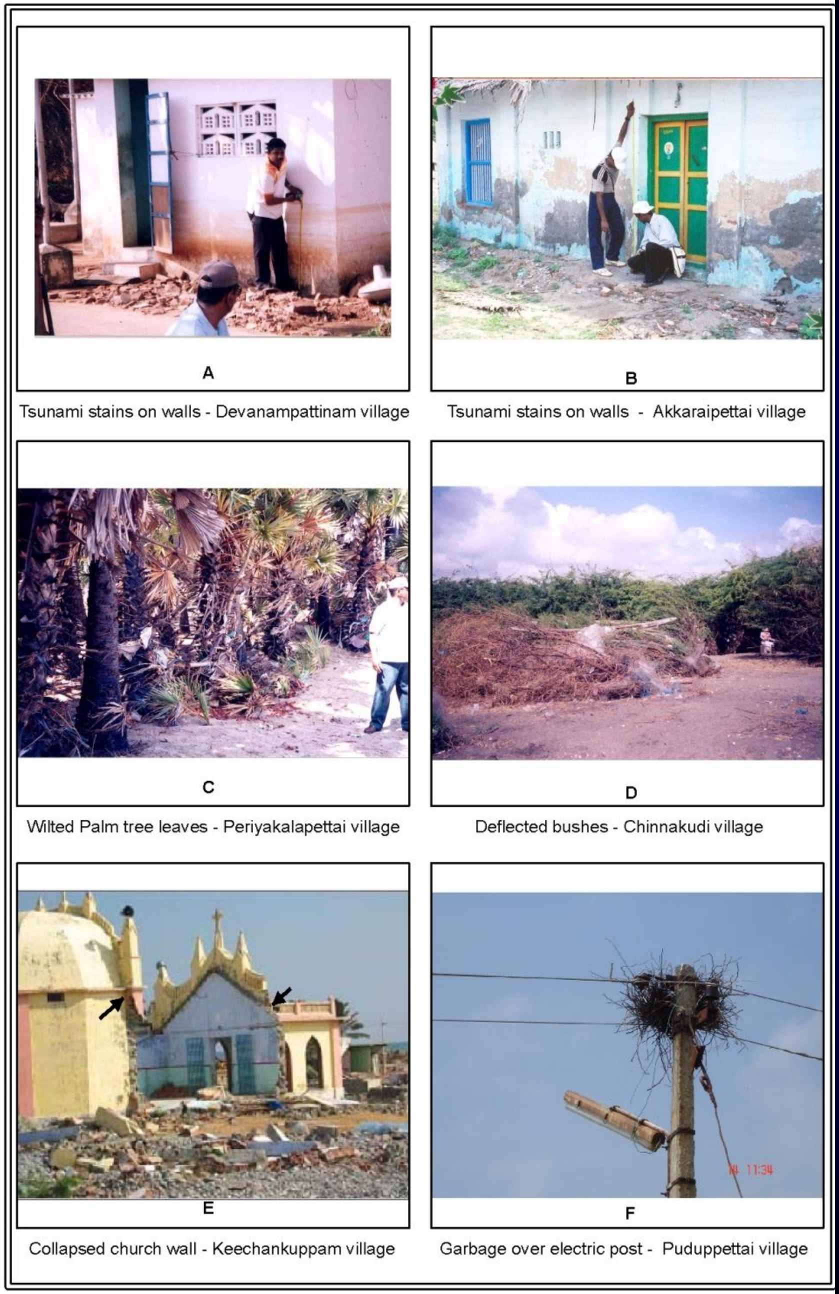
Tsunami run-up is the height above sea-level at the most inland location that the water penetrates.



Inundation distance is the distance inland from the normal shoreline that the water penetrates.

Inundation distance depends on the slope of the land extending down to the shoreline and the run-up elevation.

RUN UP MAPPING



A Tsunami stains on walls - Devanampattinam village

B Tsunami stains on walls - Akkaraipettai village

C Wilted Palm tree leaves - Periyakalapettai village

D Deflected bushes - Chinnakudi village

E Collapsed church wall - Keechankuppam village

F Garbage over electric post - Puduppettai village

Fig.4.5 Run up mapping

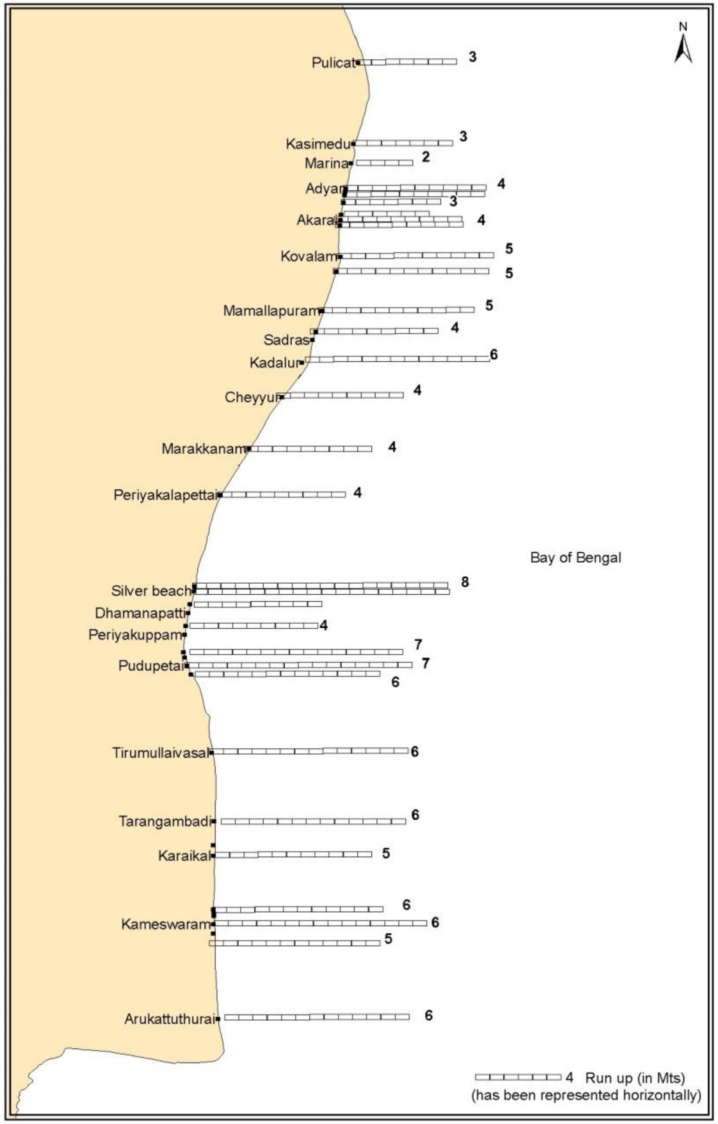


Fig.4.6 Run up

The extent of vertical rise of sea water during tsunami is called as run up

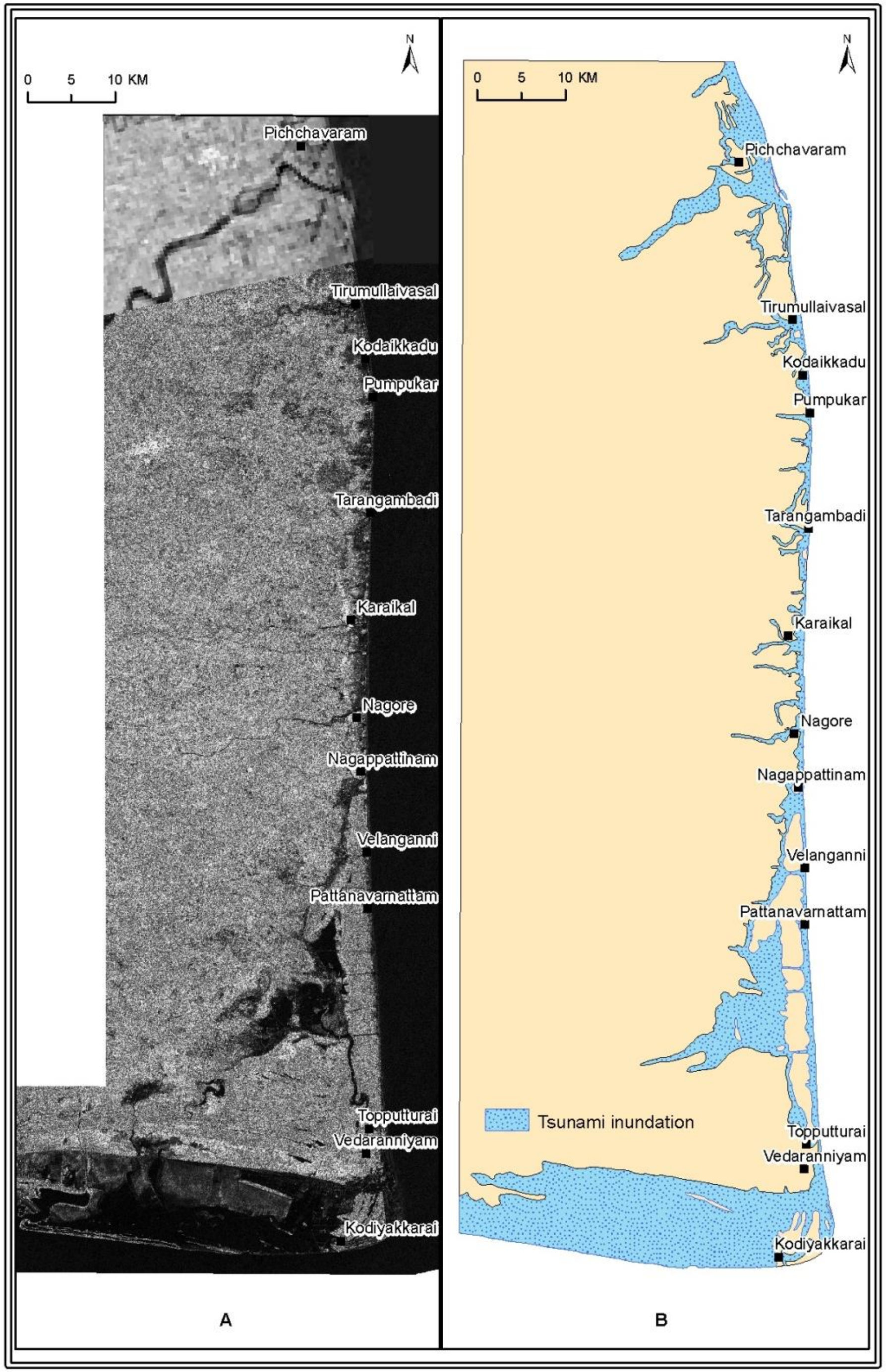


Fig.4.7 ENVISAT- Tsunami inundation

INUNDATION MAPPING

The lateral extent up to which the tsunami waters inundated into the inland is called as inundation

The microwave data of ENVISAT possesses strong credibility in mapping the tsunami inundated areas in the form of fine texture and darker tone (due to moisture content).

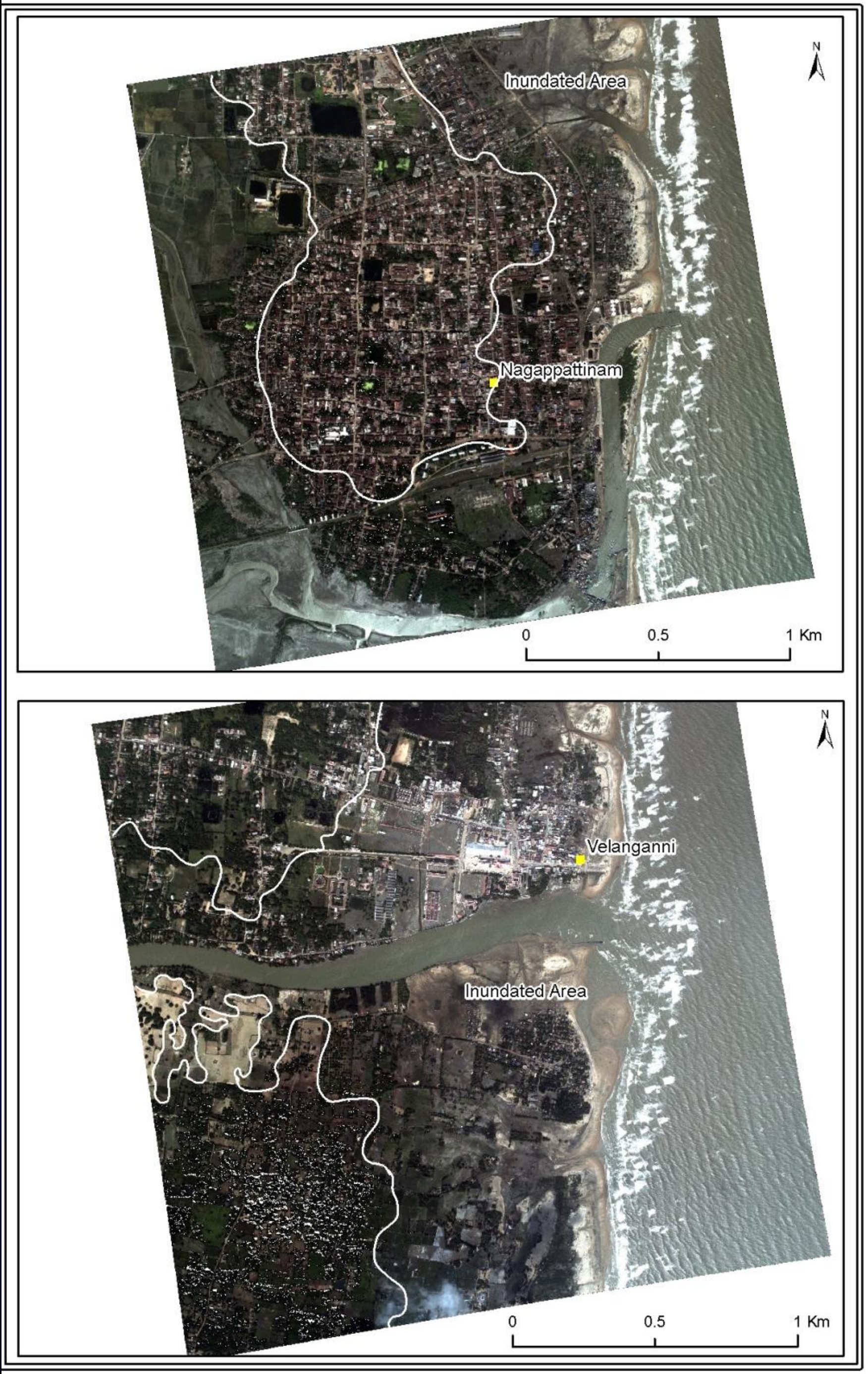


Fig.4.8 Digital ortho photograph of Nagapattinam area showing tsunami inundation

Immediately after the tsunami 2004, the digital ortho photography was done through a special flight by the Survey of India on 28-12-2004 (just two days after the tsunami) covering a width of 2 km across the east coast of India in the tsunami affected states of Andhra Pradesh and Tamil Nadu.

As these digital ortho photographs have vividly and precisely displayed the inundation pattern, the same were used for selected areas wherever the ENVISAT data did not give much clarity.

Some sample ortho photographs of parts of Nagapattinam area

(A) Thrown off boats along railway track - Nagore

(B) Thrown off boats - Cuddalore old town

(C) Thrown off boats - Muvakkarai village

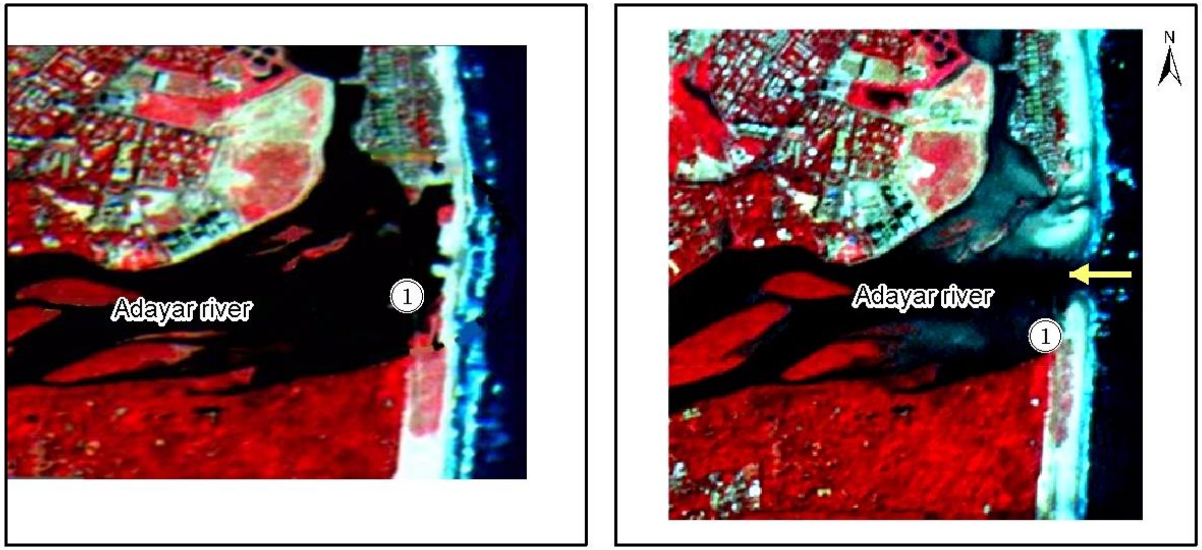
(D) Collapsed railway line - Nagore

(E) Collapsed railway line - Nagore railway station

(F) Thrown off boats - Vanjiyur village

Fig.4.10 Field photographs showing imprints of tsunami

Apart from preparing tsunami inundation maps using satellite data and the digital ortho photographs, field based mapping was also done so as to check and update the interpreted data and also to collect data on the types of damages / imprints left by the tsunami so as to bring out the ferocity, the pattern of inundation and the responses of the various geo and anthropogenic systems



(A) IRS P6 Image - 12 January 2004 (pre tsunami)

(B) IRS P6 Image - 27 December 2004 (post tsunami)

(C) IRS P6 - 12 January 2004 (pre tsunami)

(D) QUICKBIRD PAN 31 December 2004 (post tsunami)

Fig.4.11 Pre and Post tsunami changes in river mouths in the form of breakage of bay mouth bars

(A) Eroded beach - Cuddalore

(B) Eroded beach being under protection
- Pudupettai village (Nagapattinam area)

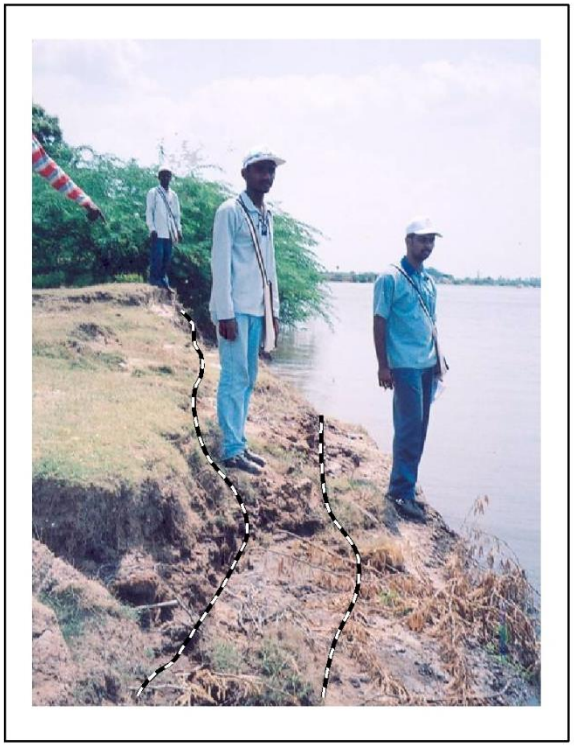
(C) Eroded beach with relict beach ridge (1)
- Uppanar river Vellangani (Nagapattinam area)

(D) Flattened beaches - Therkupoyyur village
(Nagapattinam area)

(E) Tsunami inundated Marina beach (Chennai area)

(F) Dumping of black sand - Tharangambadi
(Nagapattinam area)

Fig.4.12 Flattened and inundated beaches



(A) Tsunami cut terraces in Uppanar river - Nagapattinam

(B)Tsunami casted sediments in Uppanar river - Nagore

Fig.4.13 Tsunami cut terraces and tsunami casted sediments

(A) Damaged houses - Pudukuppam village

(B) Collapsed huts - Tirumullaivasal village

(C) Aerial view of tsunami incursed Keechakupam village

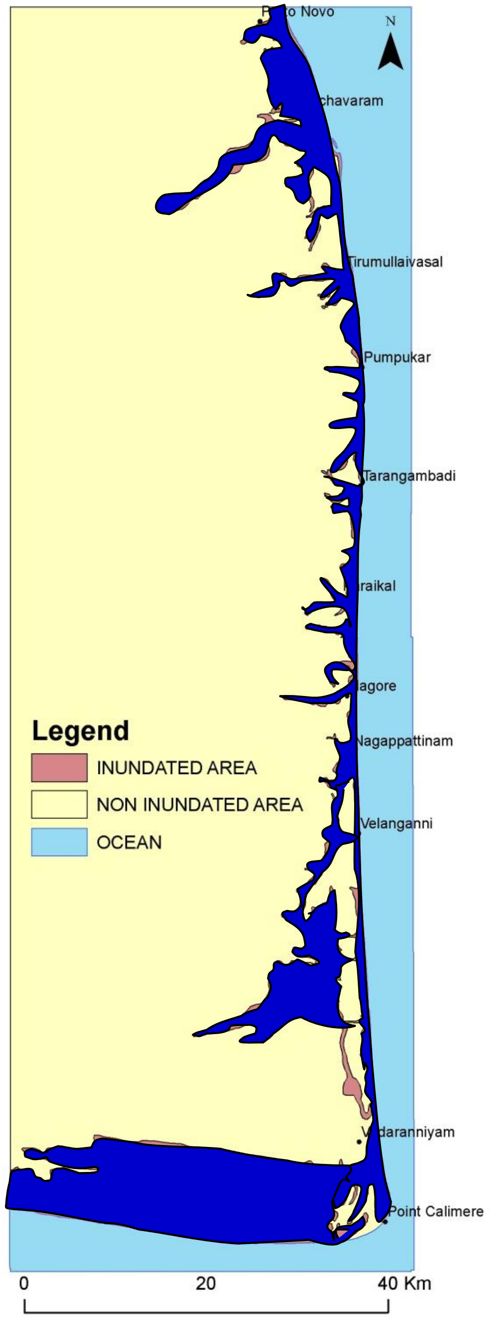
(D) Collapsed wall - Nagore

(E) Tsunami slurry encursed temple - Akkaraipettai village

(F) Garbage accumulation - Nagore railway station

Fig.4.9 Field photographs showing imprints of tsunami

NAGAPATTINAM INUNDATION MAP



Legend

- 🟥 INUNDATED AREA
- 🟨 NON INUNDATED AREA
- 🟦 OCEAN

IMPACT OF TSUNAMI OVER THE RESOURCES

(A) Tsunami incursed agriculture field - Pattanavarnattam village (Nagapattinam area)

(B) Tsunami incursed agriculture field - Kodaikkadu village (Nagapattinam area)

(C) Tossing of fishes in paddy field - Vellapalam village (Nagapattinam area)

Fig.4.14 Tsunami incursed agriculture fields

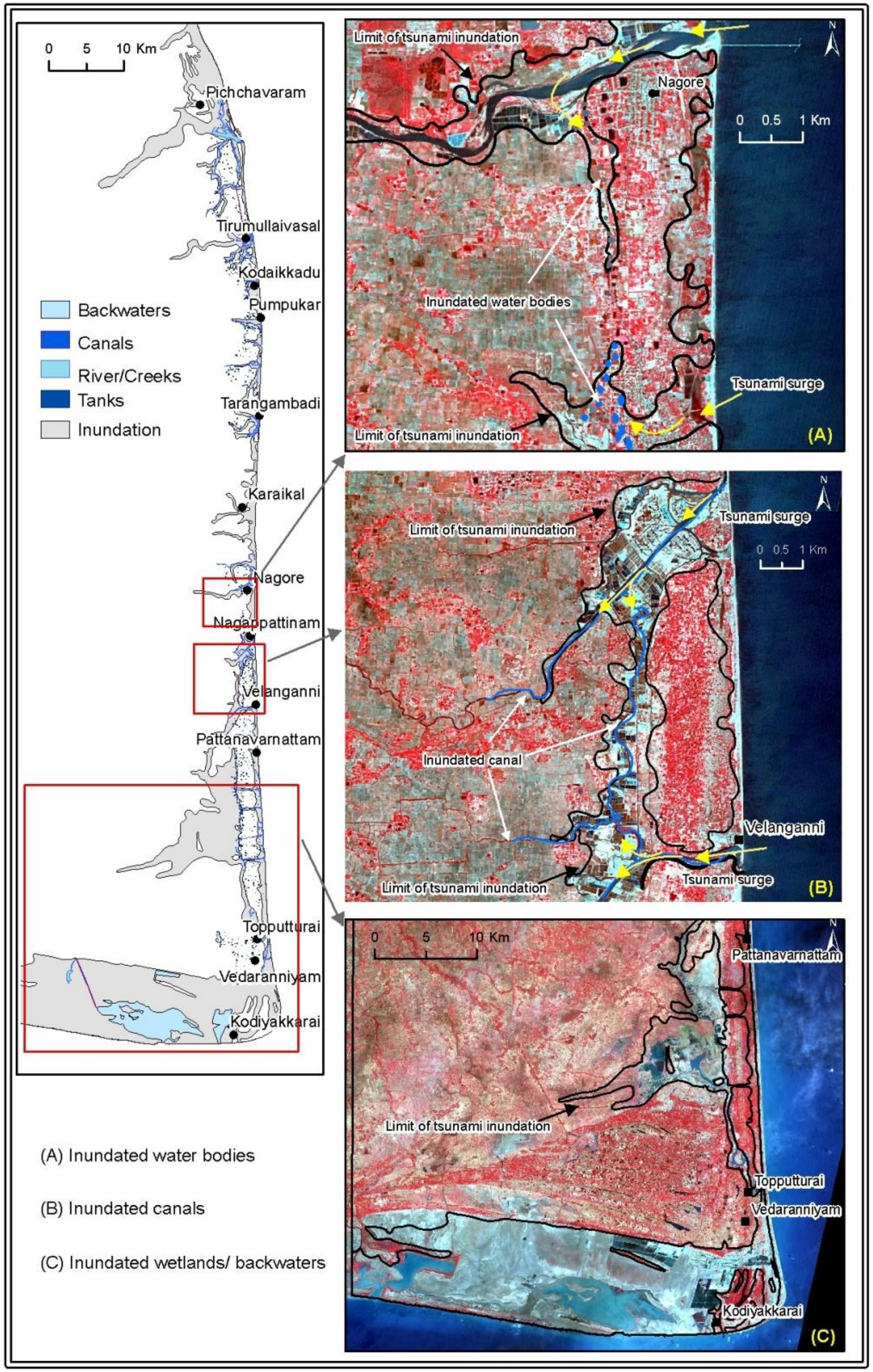


Fig.4.15 Tsunami impact over surface water resources and wetlands

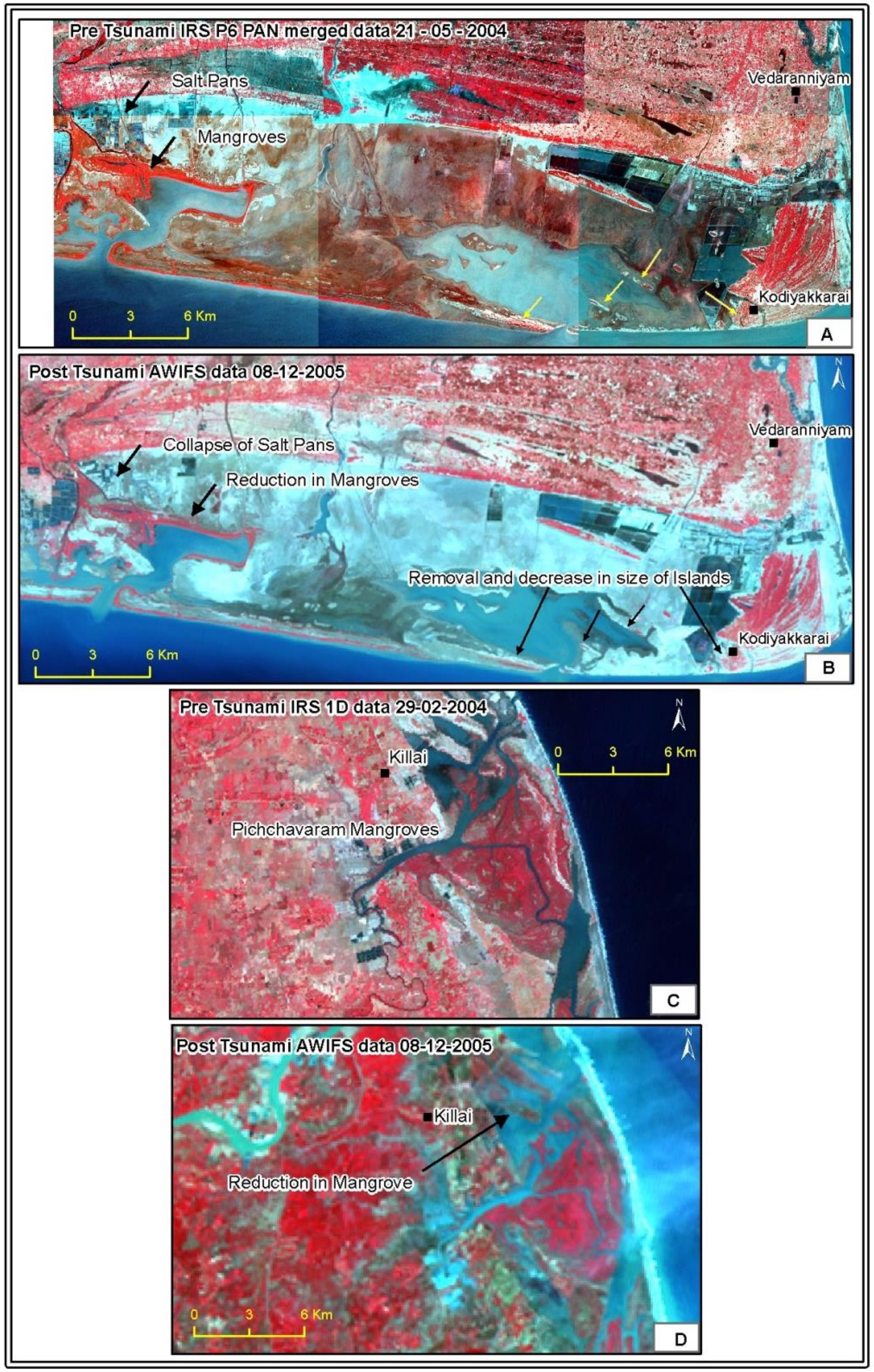
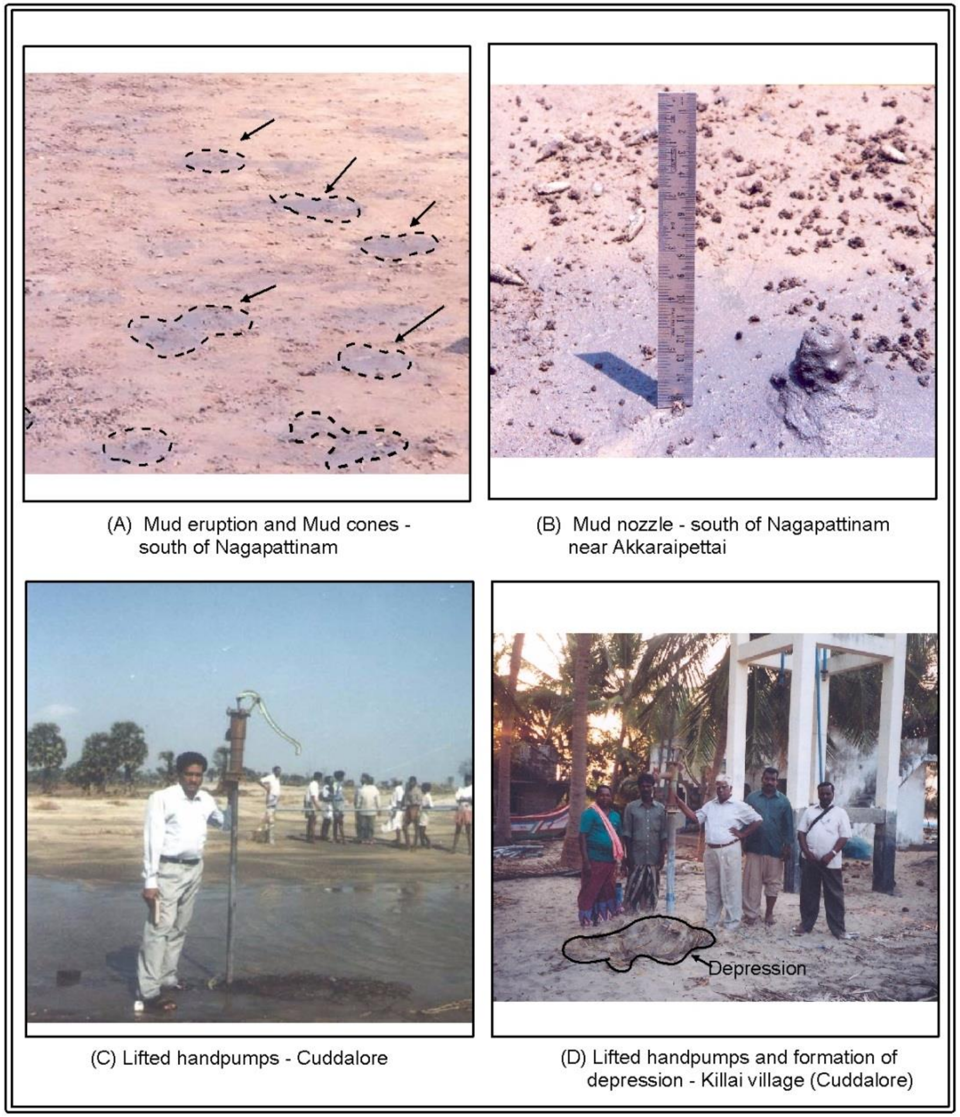


Fig.4.16 Modifications in wetland ecosystem



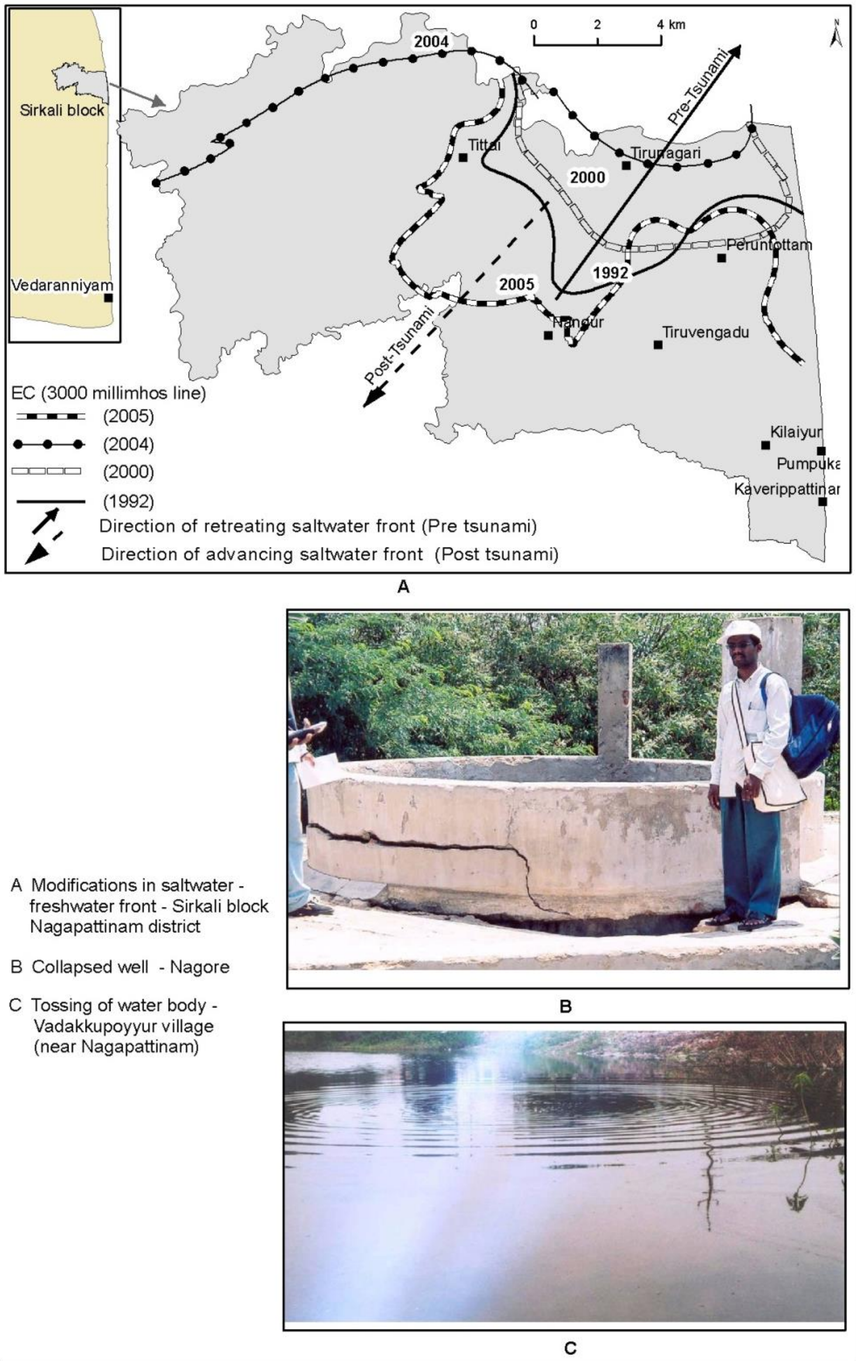
(A) Mud eruption and Mud cones - south of Nagapattinam

(B) Mud nozzle - south of Nagapattinam near Akkaraipettai

(C) Lifted handpumps - Cuddalore

(D) Lifted handpumps and formation of depression - Killai village (Cuddalore)

Fig.4.17 Tsunami impact over groundwater systems



A Modifications in saltwater - freshwater front - Sirkali block Nagapattinam district

B Collapsed well - Nagore

C Tossing of water body - Vadakkupoyyur village (near Nagapattinam)

Fig.4.18 Tsunami impact over groundwater systems

Damaged fish chilling plant - Devanampattinam (Cuddalore)

Collapsed drinking water tank - Cuddalore

Destroyed fishing harbour - Nagapattinam

Washed away railway track - Nagore

Collapsed childrens park - Nagapattinam

Destroyed electric post - Nagapattinam

Fig.4.19 Physical resources damage

Subsequent to the mapping of tsunami run up, inundation and the imprints of tsunami over land, water and physical resources, their pattern of response to tsunami were elucidated through modeling studies for carving out strategies for mitigation.

Infact, the tsunami run up pattern has shown a greater variance from area to area and the inundation too has varied from few hundred meters to a couple of kilometers and more along the rivers, creeks and estuaries.

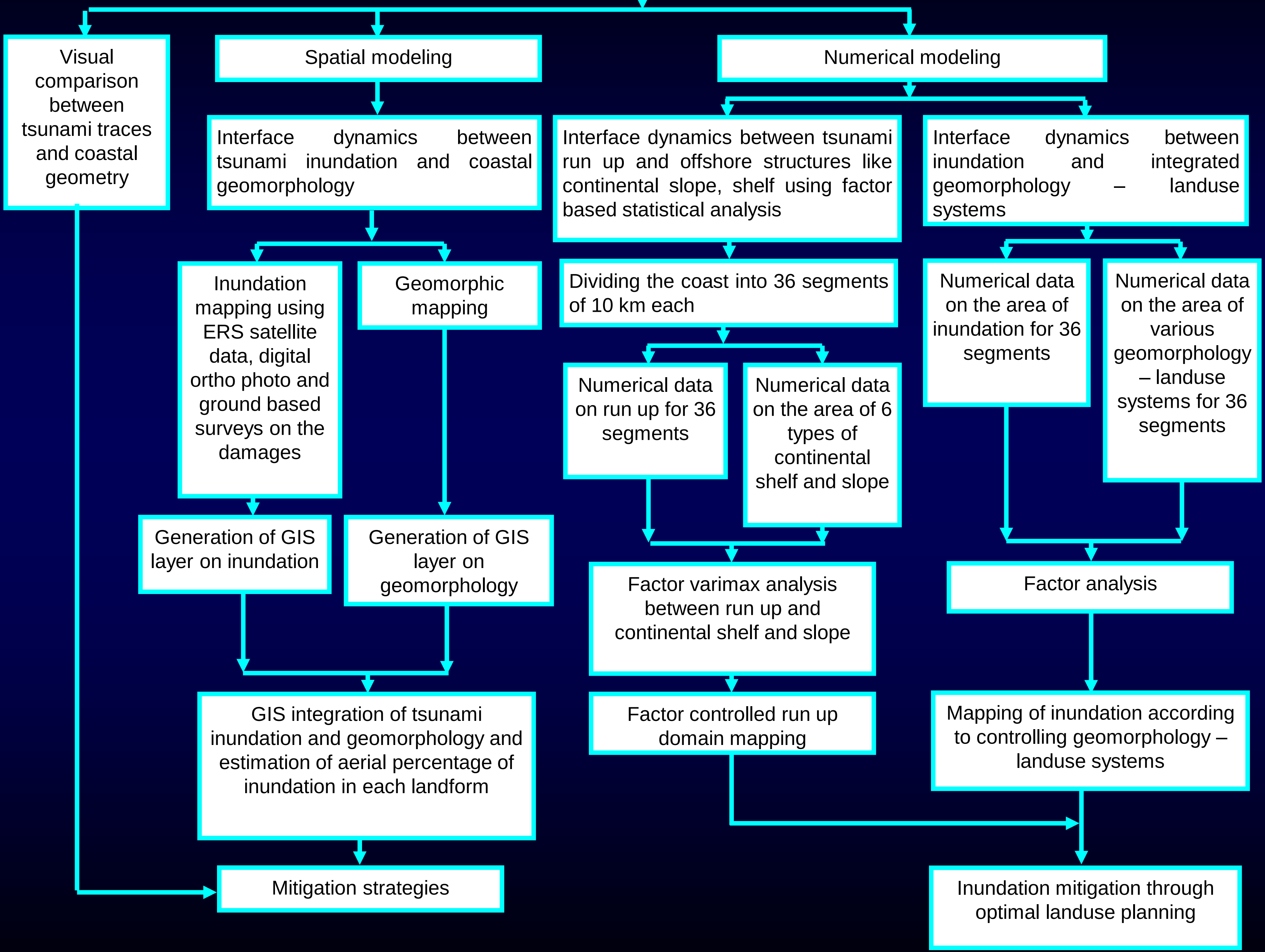
The coastal geosystems in general have shown varied responses. For example, the bay mouth bars have safely surrendered to the tsunami attack and facilitated the free entry of tsunami surge into the river systems. While, the rectilinear river courses have carried the tsunami surge for a longer distance, the compressed drainages suffered to greater erosion along their banks. Similarly, the stabilised beaches seem to have resisted the tsunami surge as seen from the tsunami cut terraces in certain areas.

Wherever these beaches were loose and uncemented, they were totally flattened out. The deflections and the directions of the fell down and uprooted trees and bushes in some beaches indicated the possible eddying of the tsunami surge which might be due to the efforts made by the beach sands to dissipate and absorb the tidal energy. Similarly, the huge backwaters have accommodated the tsunami surge.

All these indicated that the tsunami did not just lash on to the shore and land, the coastal geometry, geomorphology and landuse / land cover have interacted differently to tsunami surge.

Hence, at the next stage, an attempt was made to elucidate the interface dynamics between the coastal geometry, geomorphology, land use / land cover and the tsunami surge. Again, in order to fairly understand the pattern of tsunami run up, the offshore features like continental shelf and slope were also studied in detail and accordingly a suitable methodology was carved out

TSUNAMI RUN UP – INUNDATION MODELING AND MITIGATION



Visual comparison between tsunami traces and coastal geometry

Spatial modeling

Interface dynamics between tsunami inundation and coastal geomorphology

Inundation mapping using ERS satellite data, digital ortho photo and ground based surveys on the damages

Geomorphic mapping

Generation of GIS layer on inundation

Generation of GIS layer on geomorphology

GIS integration of tsunami inundation and geomorphology and estimation of aerial percentage of inundation in each landform

Mitigation strategies

Numerical modeling

Interface dynamics between tsunami run up and offshore structures like continental slope, shelf using factor based statistical analysis

Dividing the coast into 36 segments of 10 km each

Numerical data on run up for 36 segments

Numerical data on the area of 6 types of continental shelf and slope

Factor varimax analysis between run up and continental shelf and slope

Factor controlled run up domain mapping

Interface dynamics between inundation and integrated geomorphology – landuse systems

Numerical data on the area of inundation for 36 segments

Numerical data on the area of various geomorphology – landuse systems for 36 segments

Factor analysis

Mapping of inundation according to controlling geomorphology – landuse systems

Inundation mitigation through optimal landuse planning

TRAILS OF TSUNAMI AND COASTAL GEOMETRY

Deflected Pillars in Samiyapettai village (Nagapattinam area)

Deflected plants in Palar region

Deflected plants in Tharangambadi region

Fig.4.21 Trails of tsunami

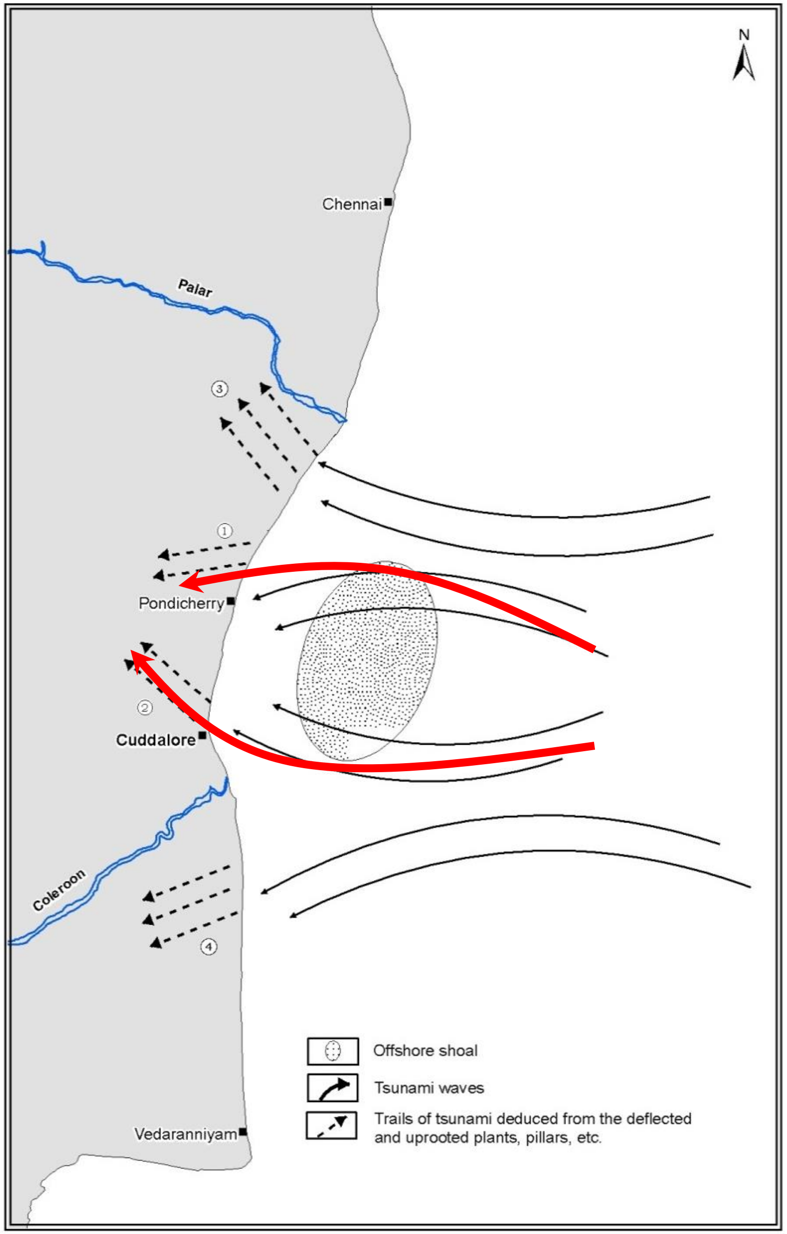


Fig.4.22 Correlation of tsunami trails and coastal geometry

SPATIAL MODELLING

INUNDATION

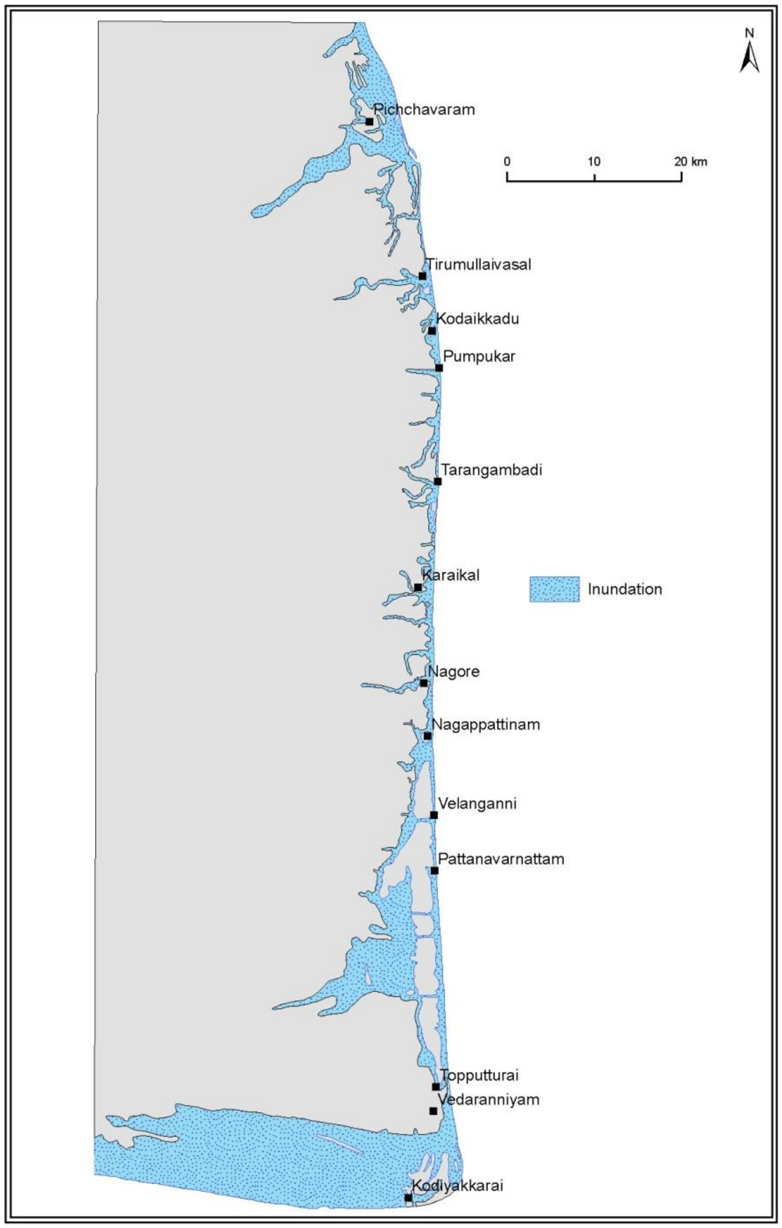


Fig.4.23 Tsunami inundation - deduced from ENVISAT satellite data and field surveys

GEOMORPHOLOGY

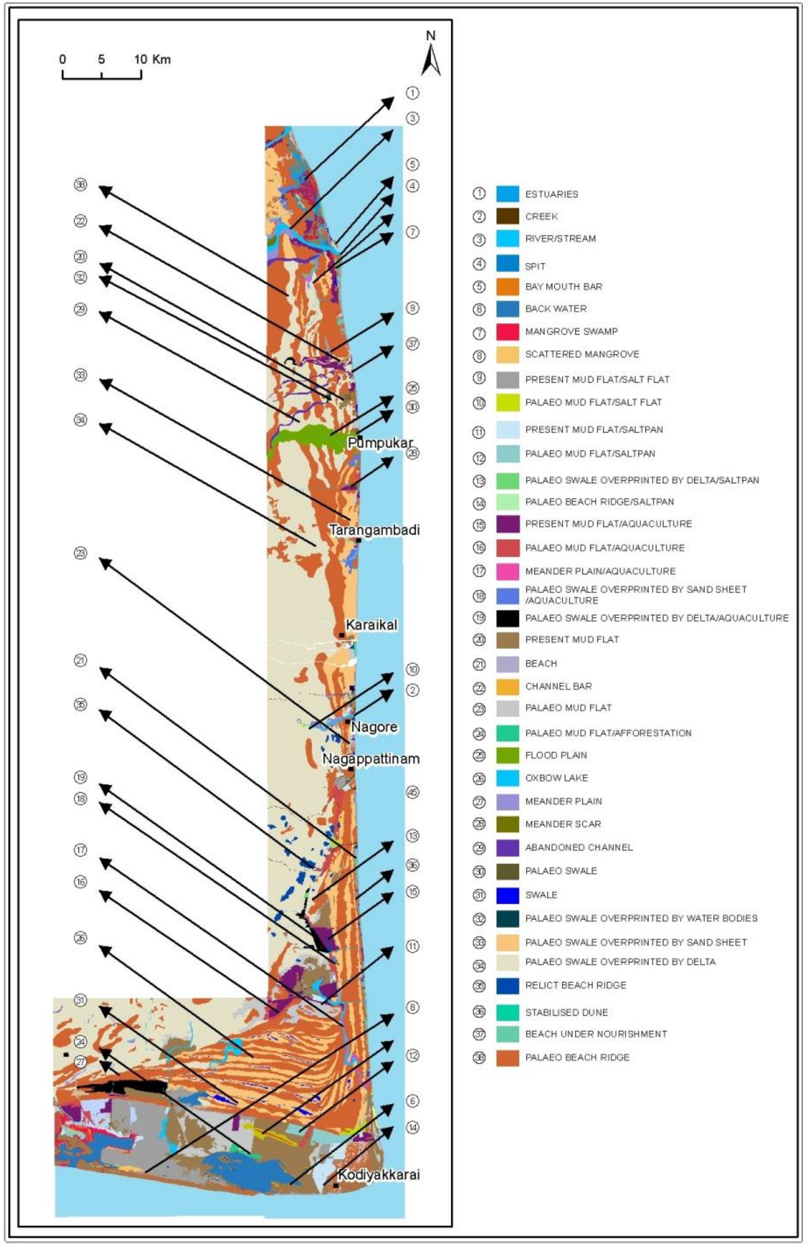


Fig 4.24 Coastal geomorphology - Nagapattinam district

INUNDATION Vs COASTAL GEOMORPHOLOGY

Sl.No	Type	Total Area (Sq.Km)	Inundated Area (Sq.Km)	Area Percentage of Damages/ Inundation
1	Estuary	9.3673	8.5064	90.73
2	Creek	5.8658	4.9523	84.43
3	River/Stream	25.1271	20.3298	80.90
4	Spit	0.0632	0.0632	100
5	Bay Mouth Bar	0.8385	0.8385	100
6	Backwater	54.5797	50.8881	93.23
7	Palaeo Beach Ridge /Saltpan	0.2121	0.0521	24.56
8	Present Mud Flat	42.4373	31.8239	74.99
9	Palaeo Mud Flat	17.5041	11.0008	62.84
10	Meander Plain/Aquaculture	3.0085	2.6073	86.66
-	-	-	-	-
-	-	-	-	-
-	-	-	-	
29	Channel Bar	0.7514	0.7514	100
30	Palaeo Mud Flat	78.5035	64.7661	82.50
31	Palaeo Mud Flat /Afforestation	2.1897	2.1897	100.00
32	Abandoned Channel	10.0656	2.2330	22.18
33	Palaeo Swale	0.3793	0.3002	79.15
34	Swale	7.3481	6.7735	92.18
35	Relict Beach Ridge	16.0938	3.2216	20.01
36	Stablised Dune	2.4850	1.5251	61.37
37	Beach Under Nourishment	7.9765	6.0355	75.66
38	Palaeo Beach Ridge	533.9091	58.1556	10.89

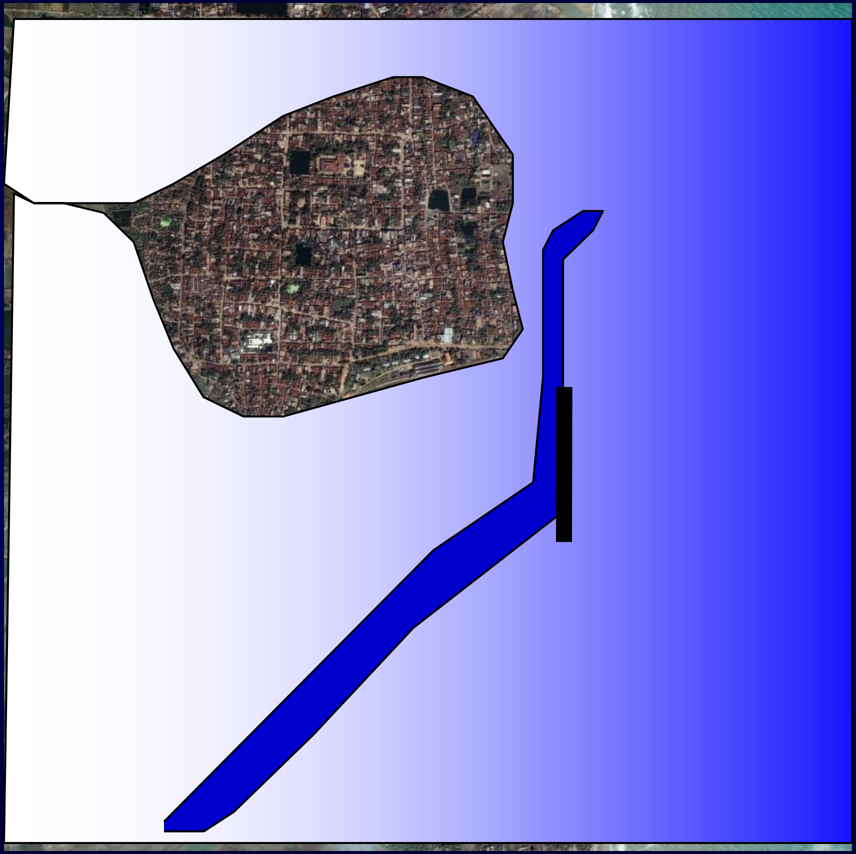
BAY MOUTH BAR - FACILITATOR

(A) Adayar River Mouth - IRS P6 Image - 12 January 2004

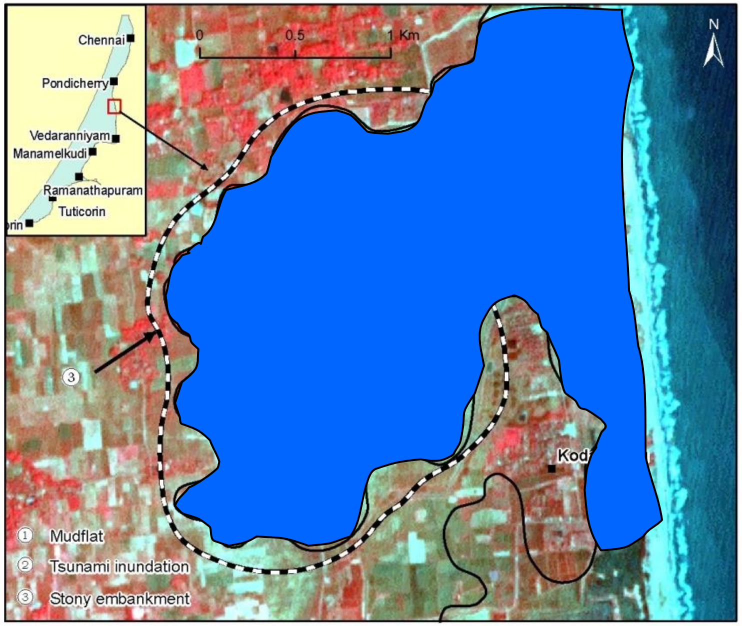
(B) Adayar River Mouth - IRS P6 Image - 27 December 2004

Fig.4.25 Bay mouth bars - Facilitators

ARREST OF RIVER MOUTH



MUD FLAT - FACILITATOR

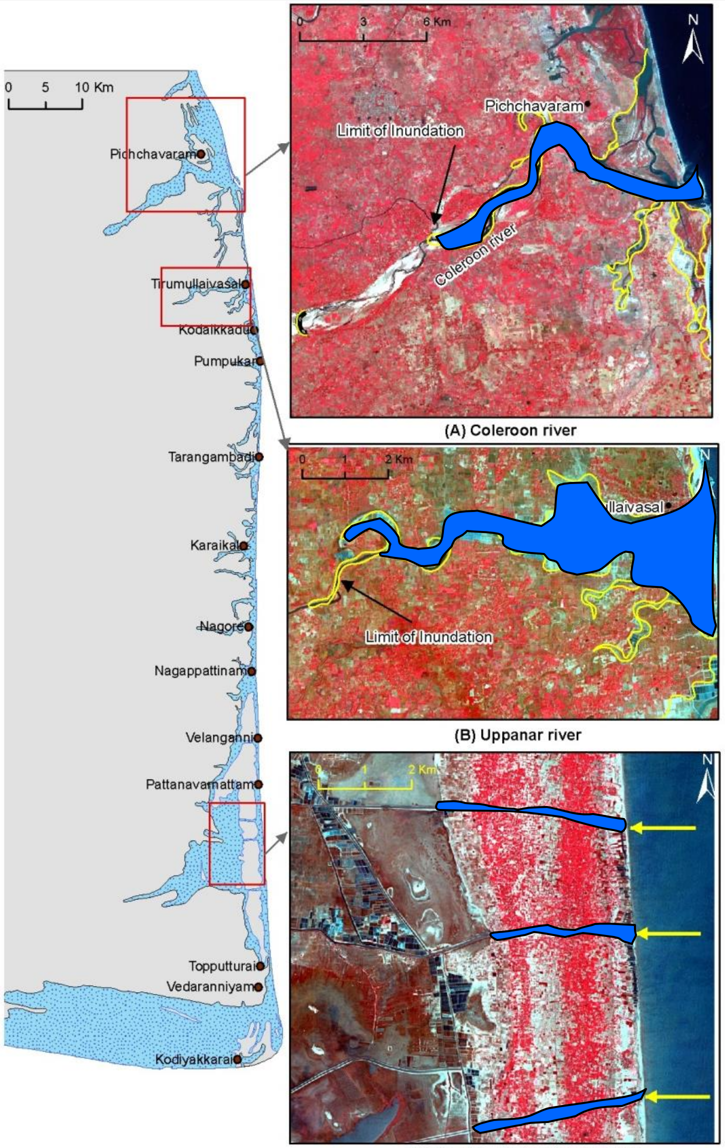


(A) IRS P6 PAN merged satellite data showing tsunami inundated mudflat at Kodaikkadu village south of Tirumullaivasal

(B) Stony embankment at Kannaki temple (Pumpuhar)

Fig.4.28 Mudflats - Facilitators of tsunami inundation - remedial measures

RIVER & CREEK - CARRIER



(A) Coleroon river

(B) Uppanar river

(C) Creeks - Nagapattinam area

Fig.4.29 IRS P6 image showing rivers and creeks - carriers of tsunami surge

BACKWATER – ACCOMODATOR
BEACH - ABSORBER

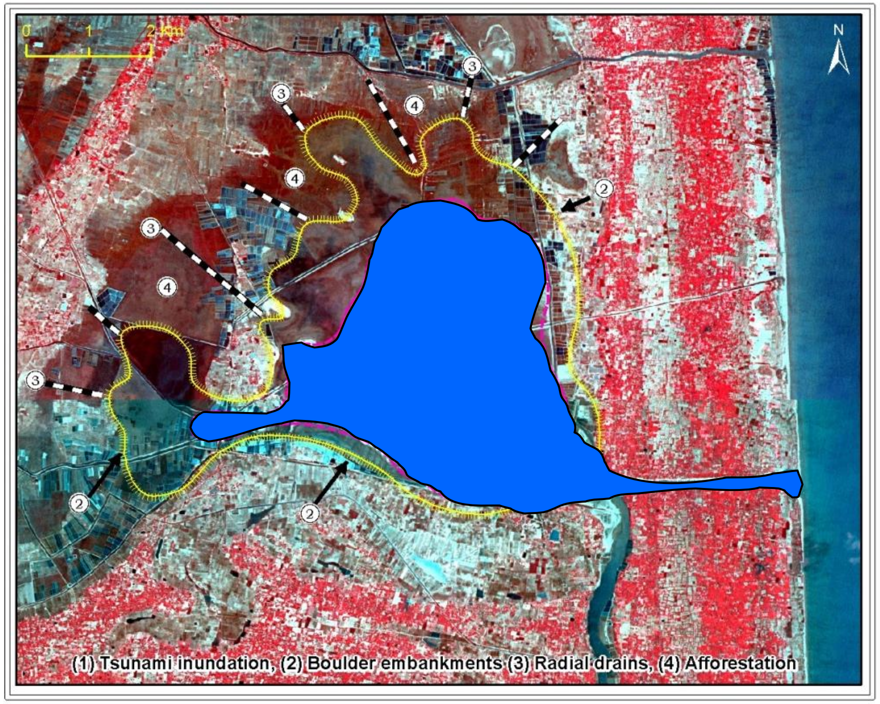
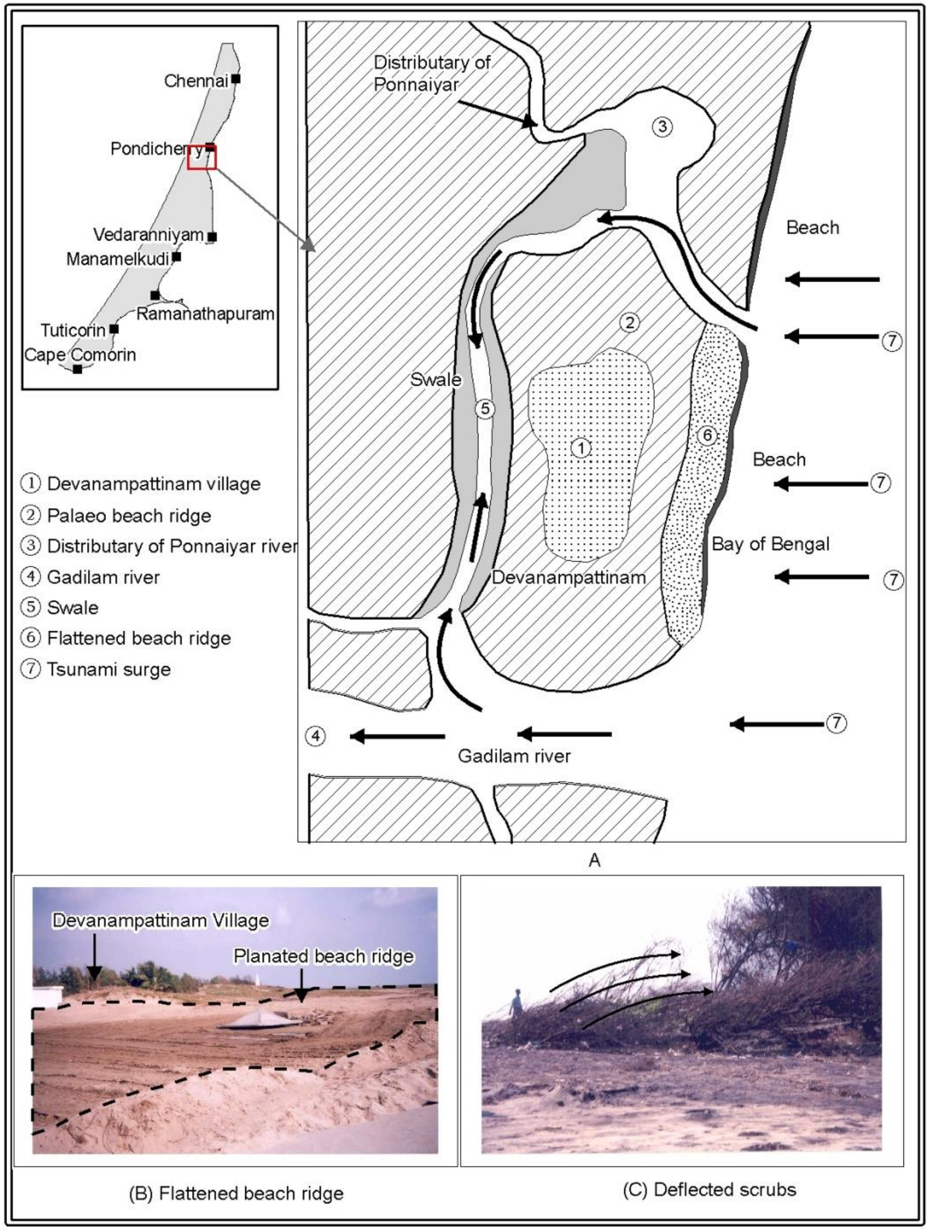


Fig.4.30 IRS P6 PAN merged image showing backwater - accommodators of tsunami surge

Fig.4.31 Photograph showing Marina beach - absorbers of tsunami surge

DESTRUCTION OF BEACH RIDGE



A

(B) Flattened beach ridge

(C) Deflected scrubs

Fig.4.32 Devanampattinam damage due to beach ridge destruction

GEOMORPHOLOGY vs TIDAL INUNDATION – MITIGATION STRATEGIES
(Few examples)

S.No	Geomorphic Features	Mitigation Strategies
1	*FACILITATORS* a)River mouths, creek mouths, Bay mouth bars and spits b)Mudflats and saltpans	➢To be left as such / or dredged ➢No vegetation / afforestation in bay mouth bars / spits ➢Keep the river / creek mouths open and avoid arresting of river / creek mouths by walls ➢Settlements if at all developed must be only on the southern bank of the rivers in the coastal areas of the state. ➢Mangroves development in mudflats ➢Regulating measures to minimize the faster growth of saltpans ➢Dumping of boulders and creation of protection embankments in between mudflats / saltpans and the sea

2	*CARRIERS* Creeks and rivers/streams	➢Keep mouths open ➢Afforestation along banks ➢Boulder embankment along low lying banks ➢Avoid settlements in low lying banks of rivers / streams ➢Promotion of mangroves
3	*ACCOMMODATORS* Estuary, backwaters, mangrove swamp, palaeo mudflat and swale	➢Mouths to be kept open ➢Afforestation of mangroves in the mangrove swamps and in peripheral parts of the backwaters and rims of the swales. ➢Boulder embankment along the rim of the backwaters and mangrove swamps. ➢Mangroves creations in palaeo backwater ➢Radial outward drainages from the Palaeo backwaters to the Palaeo mudflats, afforestation and promotion of bird sanctuary

4	***ABSORBERS*** Beaches	➢Existing beach nourishment by afforestation with deep rooted trees ➢Beach growth propagation by constructing groins at suitable locations and nourish such beaches too by afforestation.
5	***BARRIERS*** Palaeo and Relict beach ridges	➢Intensive Afforestation through casuarina and cashew

GEOMORPHOLOGY vs TIDAL INUNDATION – MITIGATION STRATEGIES
(Few examples)

Bay Mouth Bars → Facilitators → Not to be affected or Utilized

Mudflats / Salt pans → Facilitators → Protective boulders embankments
→ Mangroves

River mouths → Carriers → Keep the mouth open with out obstruction / blocking

Creeks → Carriers → Mangrove vegetation

Backwaters / Palaeo mudflats → Accommodators → Radial out ward drain in mud flats, vegetation, bird sanctuary

Beaches → Absorbers → To be nourished

Beach Ridges → Barriers → To be nourished/Afforested

LINEAR MODELLING – RUN UP VS OFFSHORE SYSTEMS

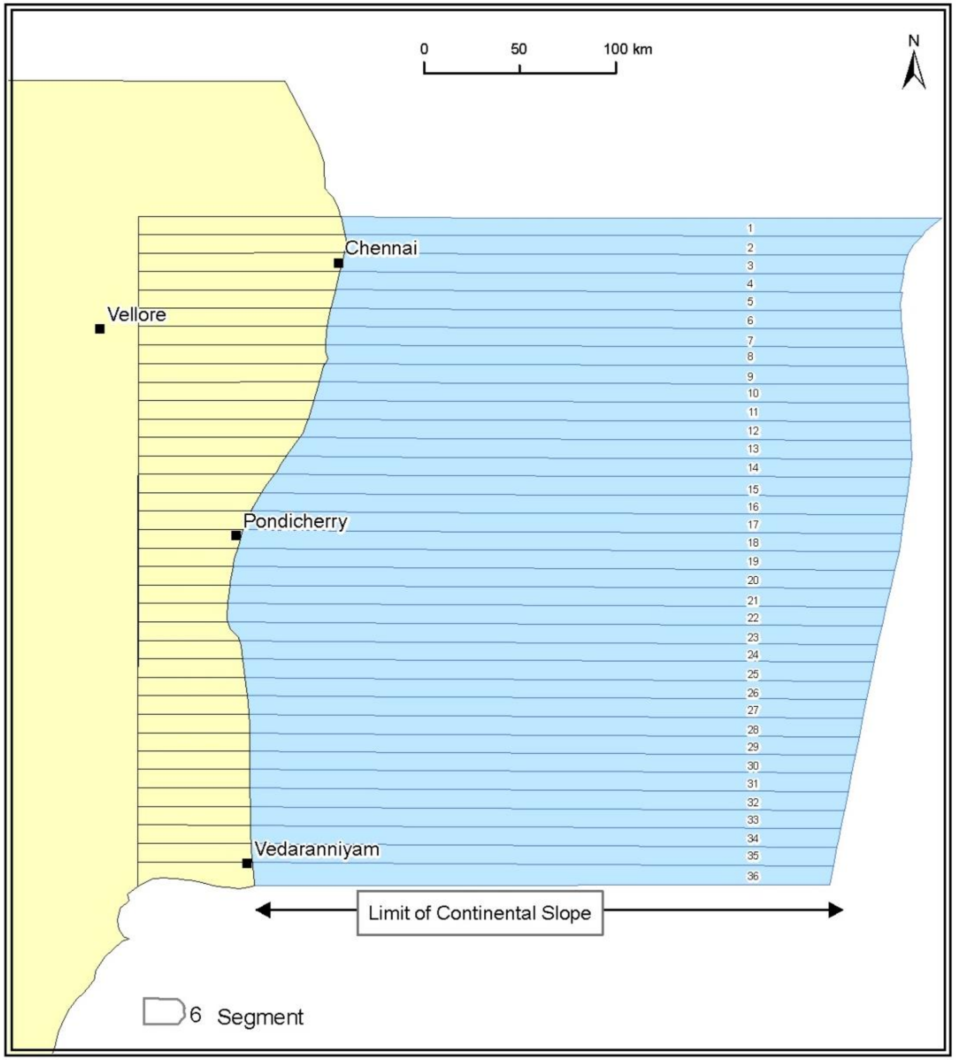


Fig.4.33 Sampling segments

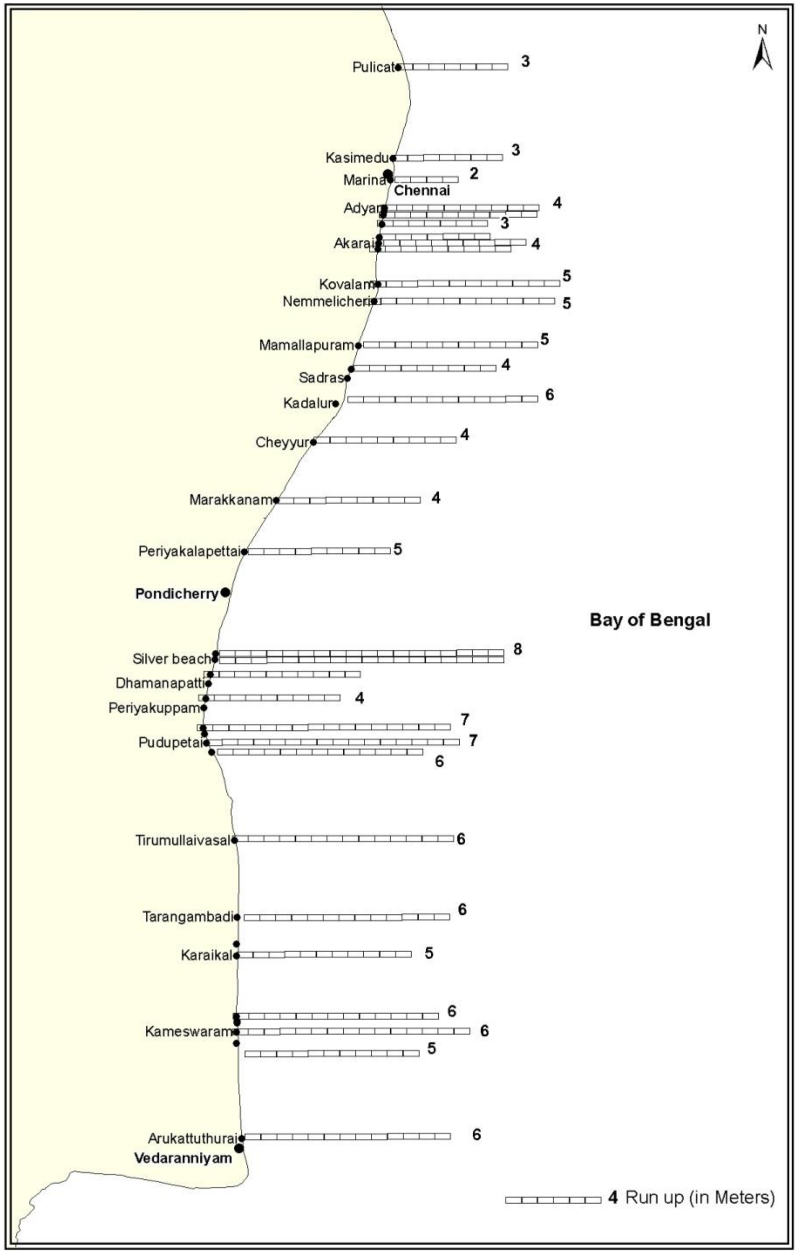


Fig.4.34 Run up (in 36 Segments)

Offshore Geosystems Scenario

The database on offshore geosystems viz: continental slope and continental shelf were generated by mapping the features from NATMO atlas.

Further, using the ETOPO satellite data which provides information on the sea bed topography,

the continental slope was sub divided into

Shallow (2 to 20 m/km) gradient
Moderate (21 to 80 m/km) gradient and the

Continental shelf into

Shallow (2 to 20 m/km) gradient,
Moderate (21 to 80 m/km) gradient and
Steep (> 80 m/km) gradient (Fig. 4.35)

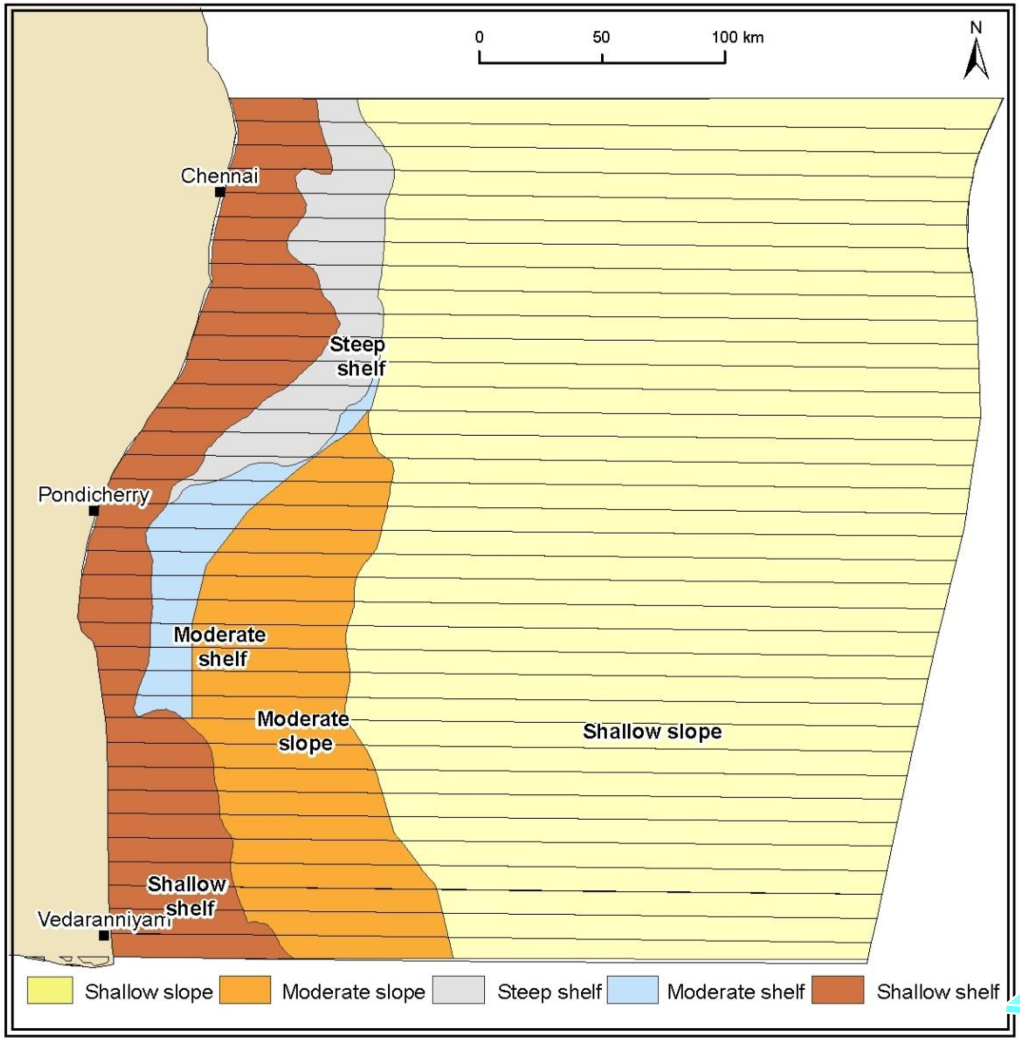
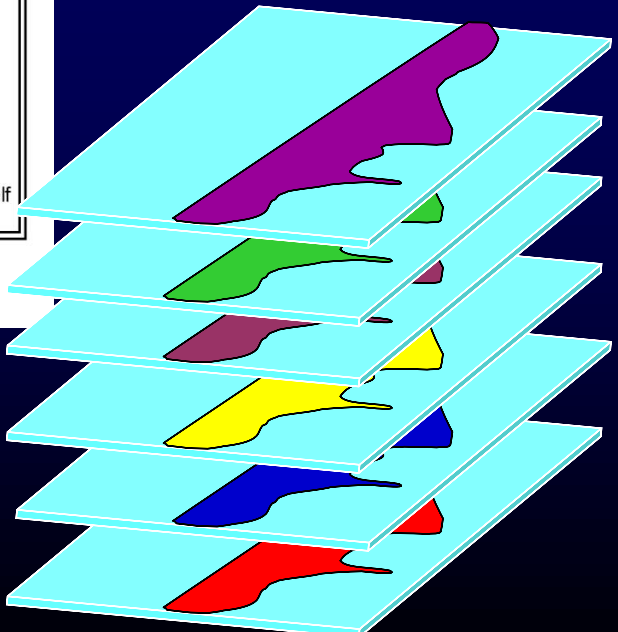


Fig 4.35 Offshore geosystem scenario

Offshore Geosystems



RUNUP 36 SEGMENTS

SHALLOW SLOPE

MODERATE SLOPE

STEEP SHELF

MODERATE SHELF

SHALLOW SHELF

Variable	Factor 1	Factor 2	Factor 3
RUN UP	.29057	-.02231	-.95420
SH SLOPE	-.74633	.55282	.08377
MOD SLOPE	.94522	.09717	-.23228
ST SHELF	-.87936	-.15855	.27077
MOD SHELF	.29819	.87240	-.09397
SH SHELF	.14308	-.92373	-.07788

EIGEN VECTORS

The run up increases with increase in the area of moderate continental slope and moderate continental shelf and The run up increases with decrease in the areas of shallow continental slope and steep continental shelf.

Run up increases

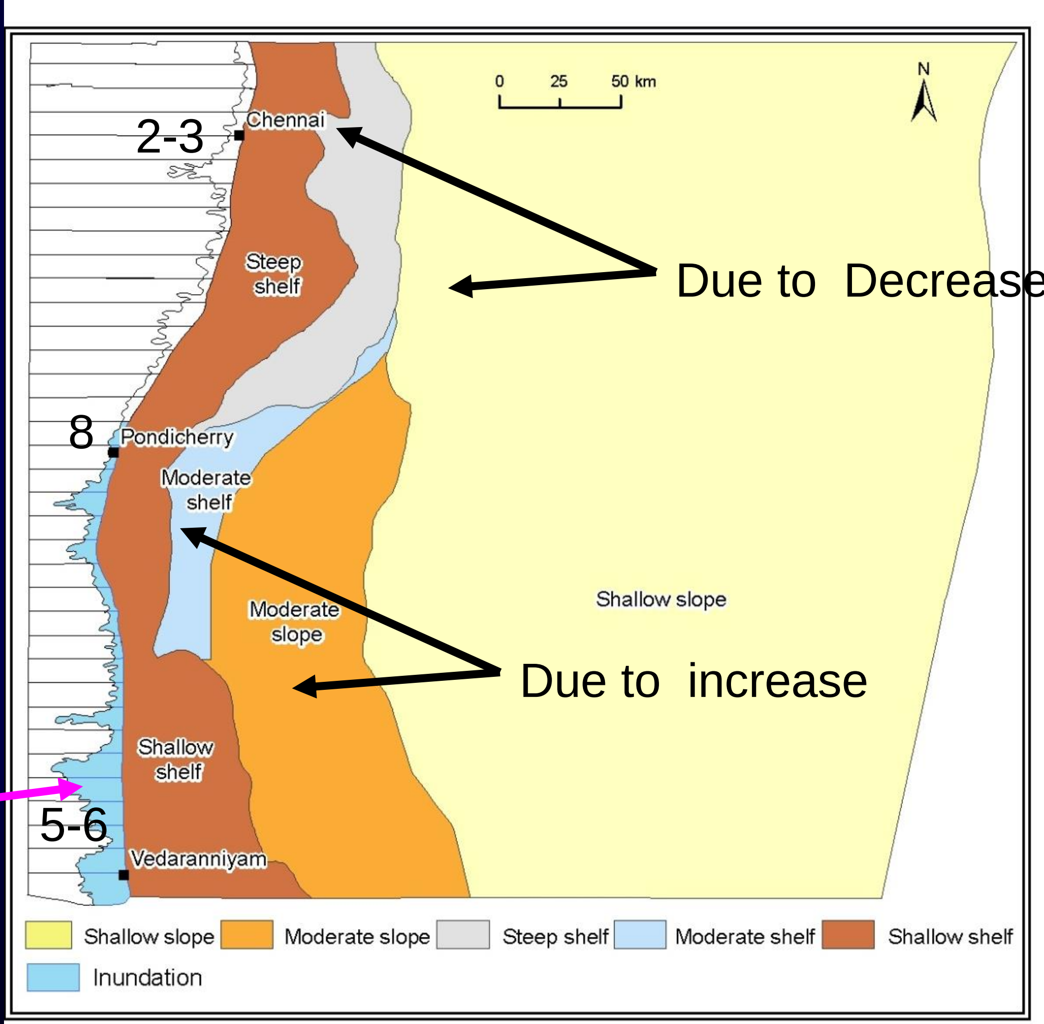


Fig 4.36 Run up vs offshore geosystems

PICTORIAL REPERSENTATION

LINEAR MODELLING – INUNDATION UP VS ONSHORE SYSTEMS

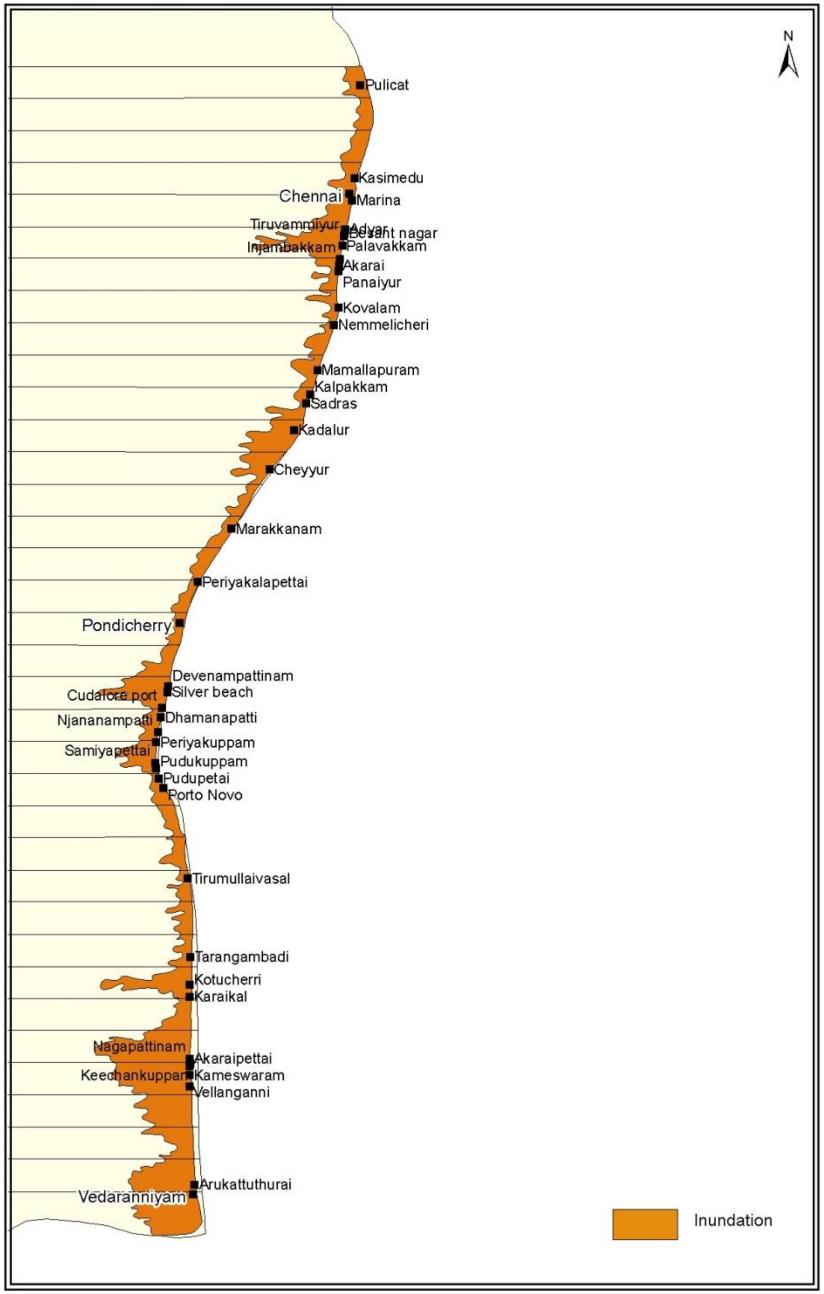


Fig 4.37 Inundation pattern

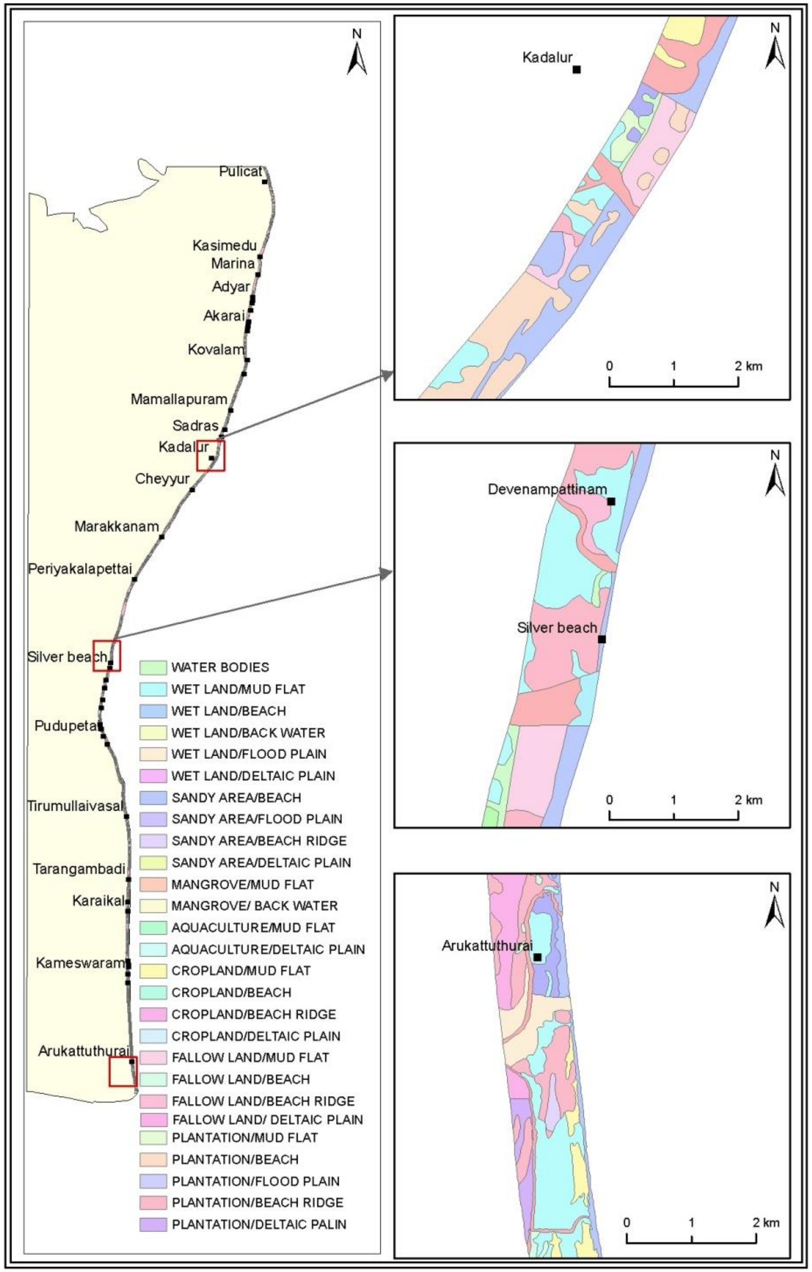


Fig. 4.40 Integrated geomorphology and landuse / land Cover

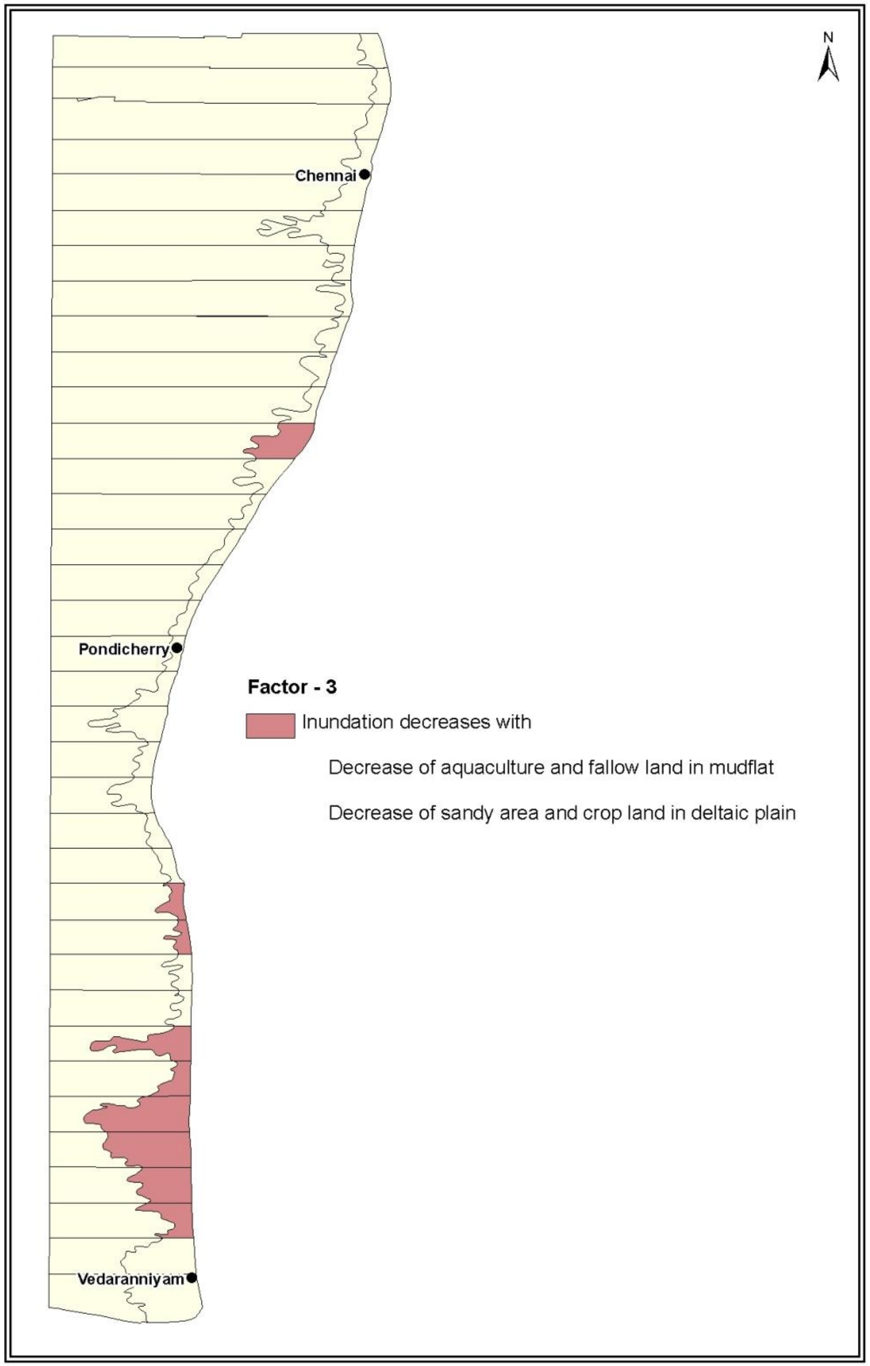


Fig.4.41 Inundation vs coastal geosystem (Factor -3)

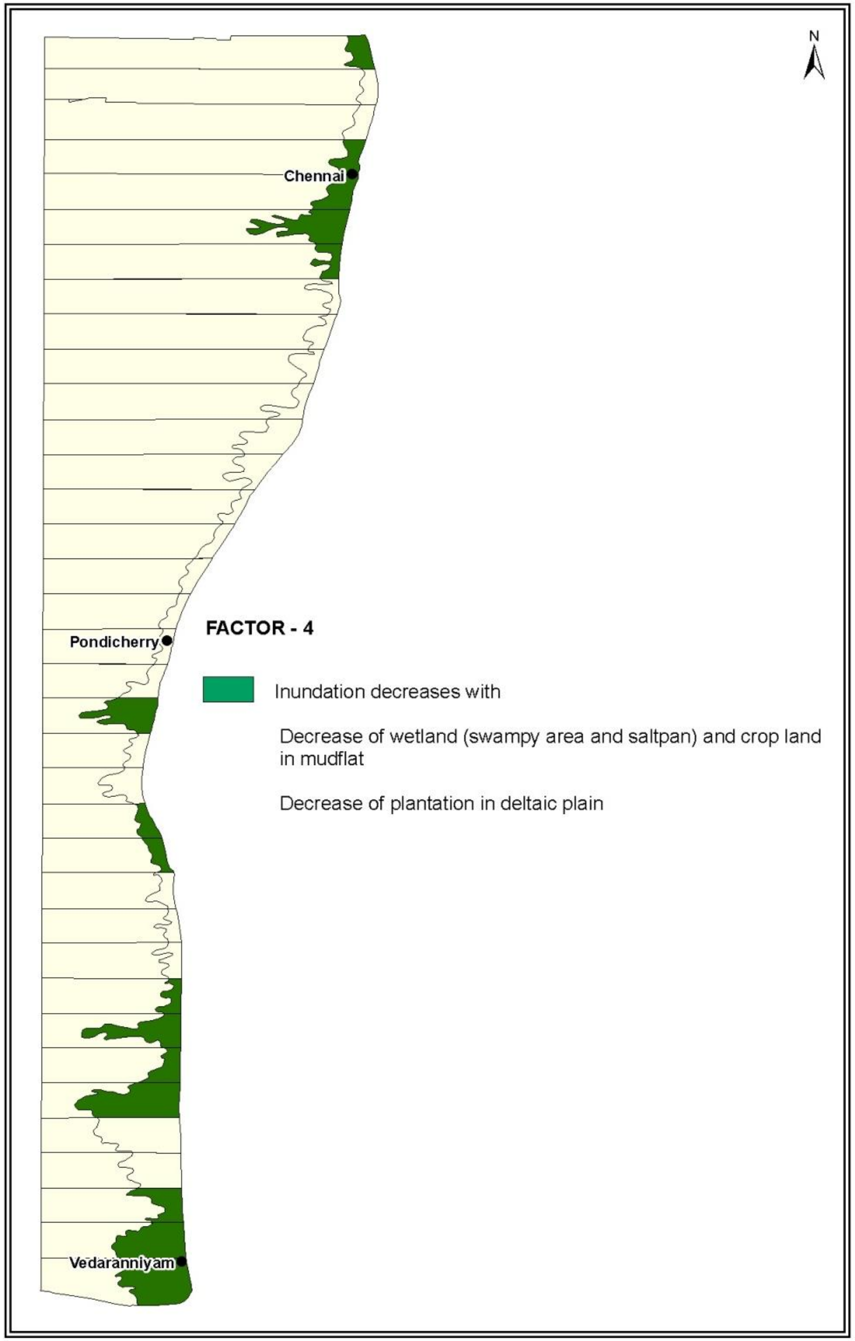


Fig.4.42 Inundation vs coastal geosystem (Factor - 4)

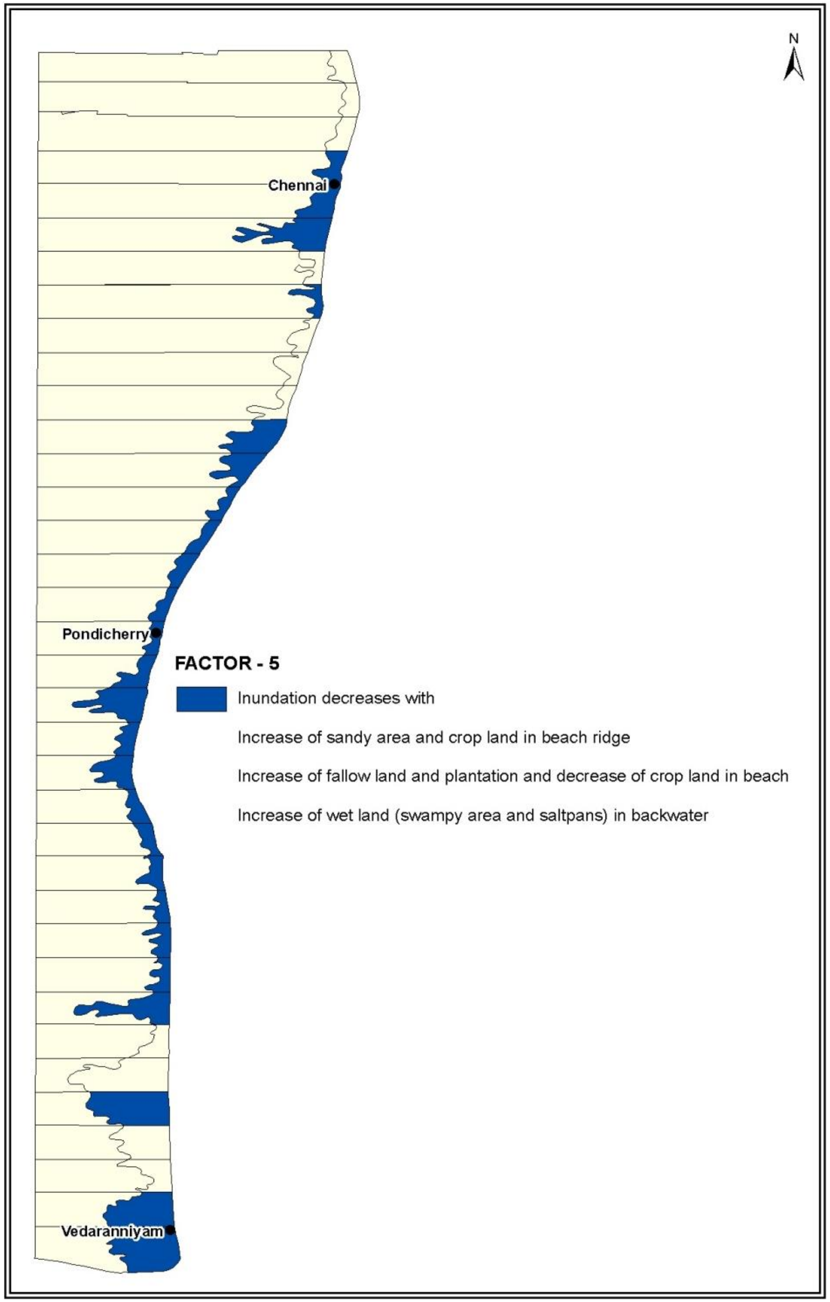


Fig.4.43 Inundation vs coastal geosystem (Factor 5)

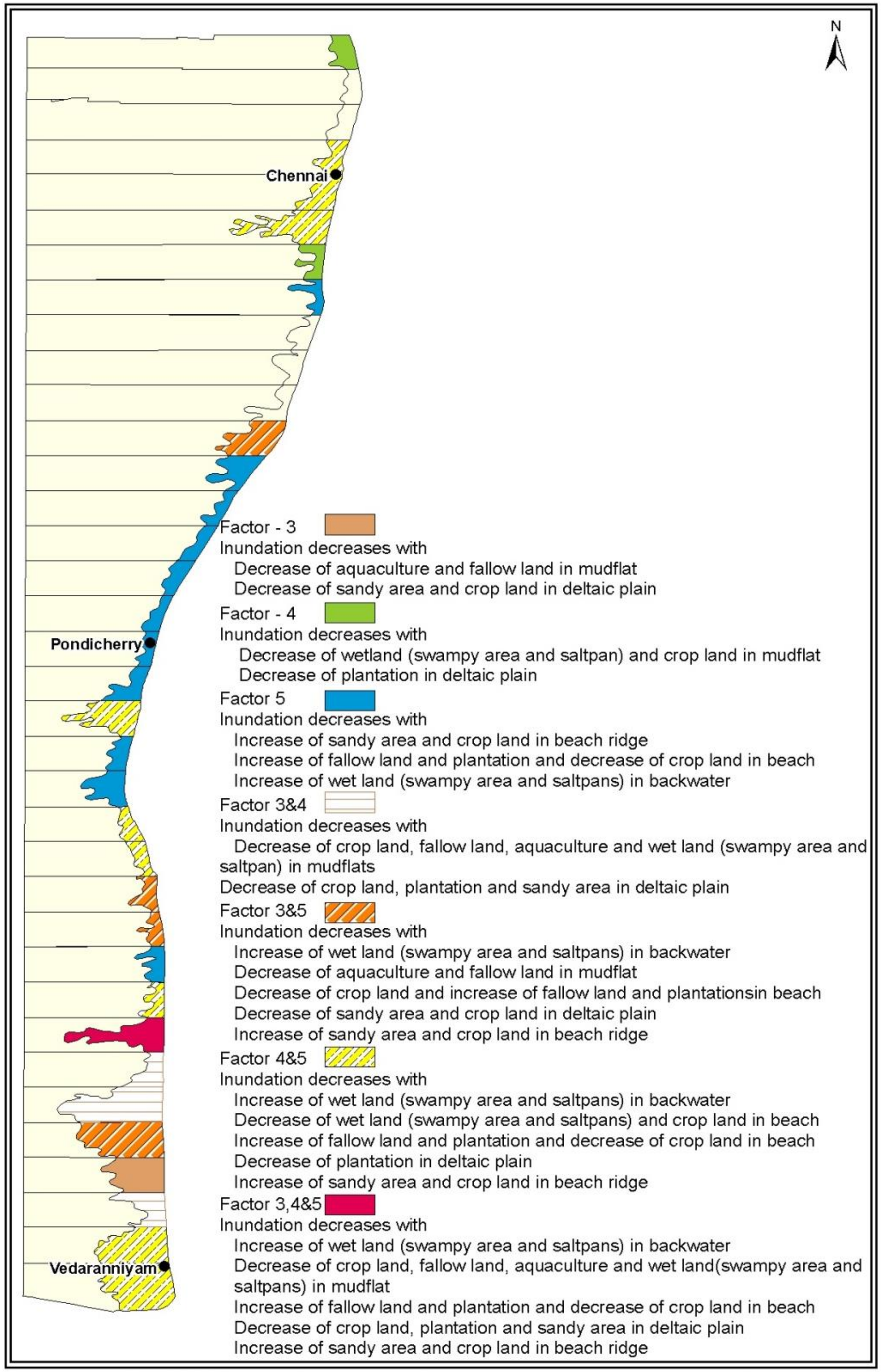


Fig.4.44 Inundation vs coastal geosystem (Integrated output)

INUNDATION DECREASES WITH

Increase in aerial extent of

Backwater and Wetland (which would have accommodated the tsunami surge)

Beach ridge with sandy area (which would have absorbed the tidal waves)

Beach ridge with Plantation (which would have dissipated and acted as barriers),

Beach with sandy area and beach with plantations (which would have absorbed as well as dissipated).

MITIGATION STRATEGIES

Creating water bodies in deltaic plains, so that surge will be get accommodated

Mangrove afforestation in suitable wetlands, so as to dissipate the tsunami energy.

Increase aquaculture in mudflats and deltaic plains and create plantations in flood plains so that tsunami energy will be dissipated.

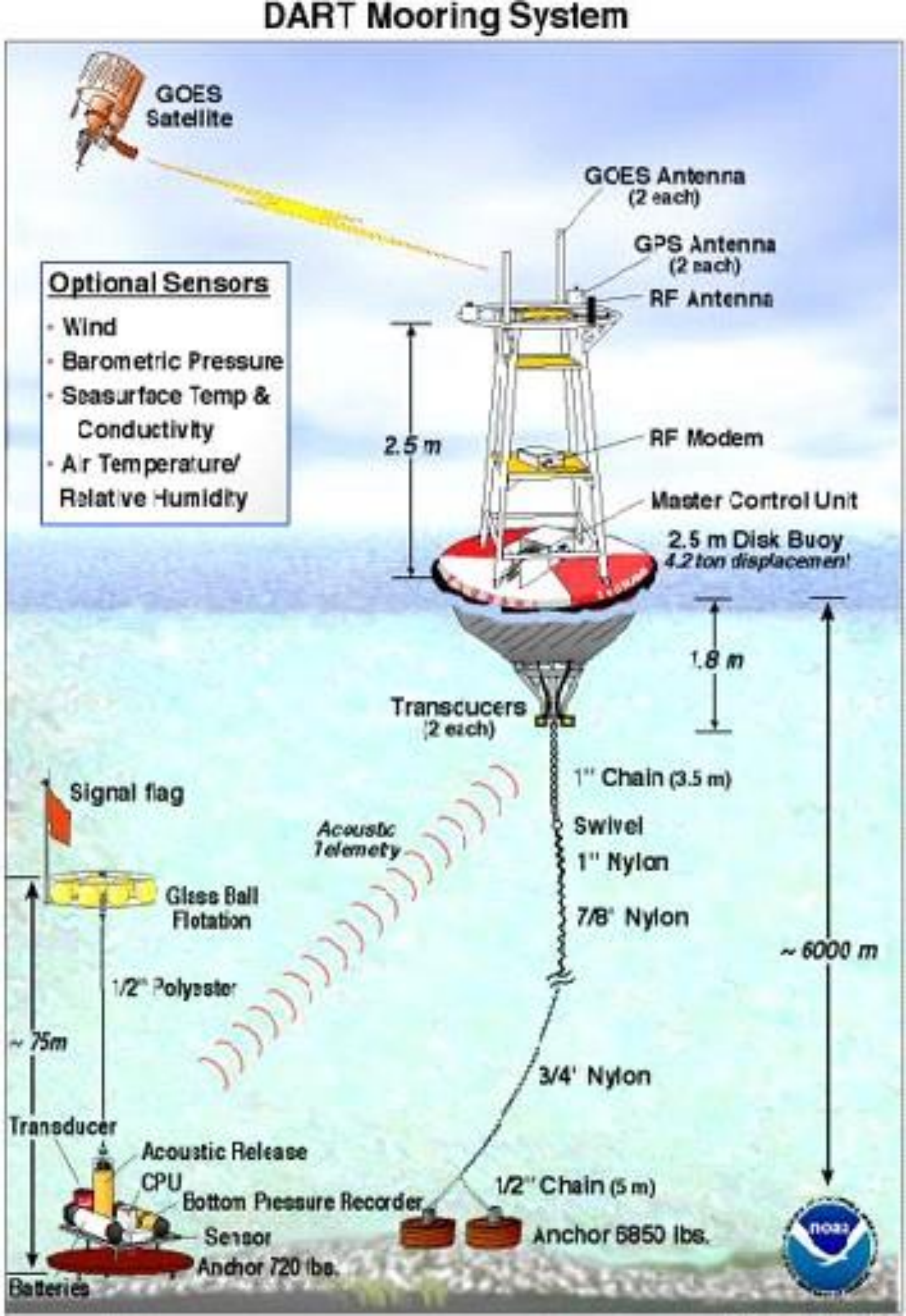
Decrease crop land in mudflat, fallow land in beach ridges in order to act as Barriers

CONCLUSION

- From the above analysis it is evident that the geosystems have responded the tsunami surge in unique fashion
- Through visual interpretation the response of coastal geometry to tsunami was brought out
- Through Spatial modelling the geomorphic features were classified as carriers, facilitators, accomodators, absorbers and barriers and accordingly mitigation strategies were eolved
- Similarly the linear modelling has brought out an unique land use / land cover based mitigation strategies.
- Through which the damages can be minimised

TSUNAMI WARNING SYSTEM

WARNING SYSTEMS



The DART project was developed by the NOAA Pacific Marine Environmental Lab (PMEL) and brought into operational use by the NOAA National Data Buoy Center (NDBC) in October 2003.

The DART project is an ongoing effort to maintain, improve the capability for the early detection, real-time reporting of tsunamis in the open ocean and reduce costly false alarms (González et al 1998).

The DART buoy system comprises two parts: the bottom pressure recorder (BPR) and the surface buoy with related electronics. The BPR is capable of detecting and measuring tsunamis with amplitude as small as 1 cm in 6000 m of water (Eble and Gonzalez 1991).

The BPR uses a pressure transducer to make 15 seconds averaged measurements of the pressure exerted on it by the overlying water column.

Data is transmitted from the buoy via an acoustic modem, and from the buoy via the Geostationary Orbiting Earth Satellite (GOES) Data Collection System.

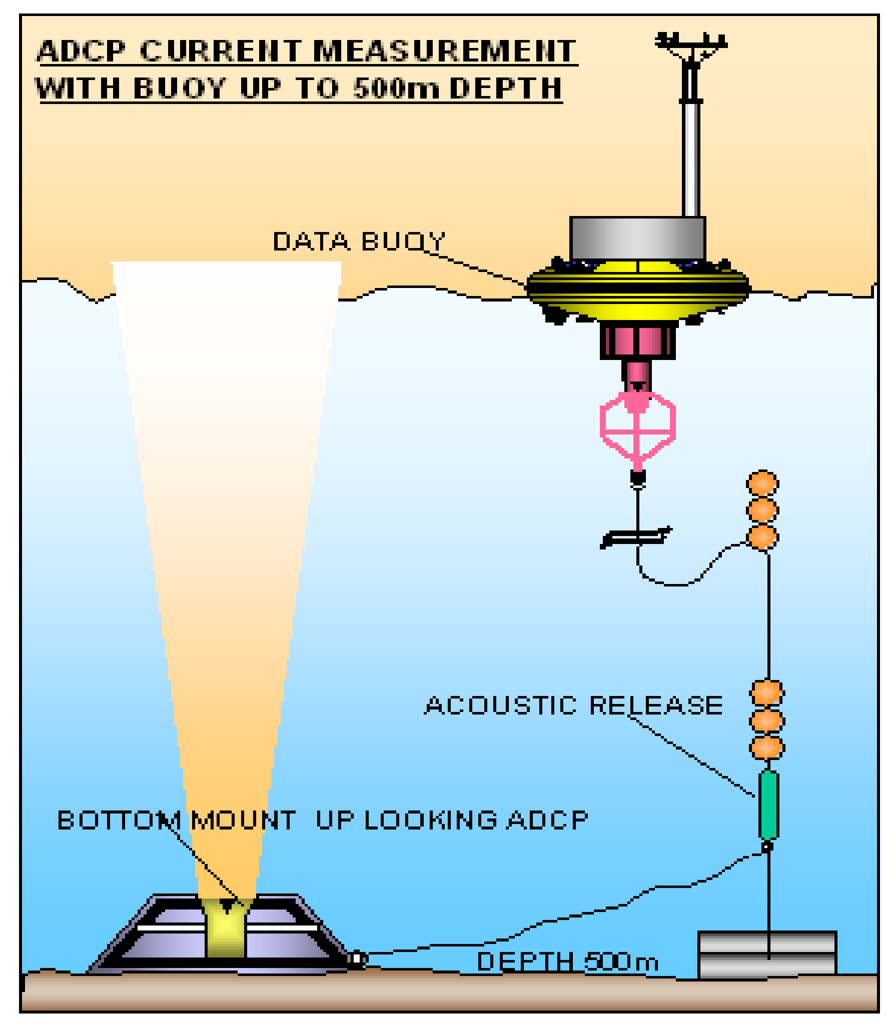
Under normal conditions (no tsunami) the BPR sends data hourly comprising four 15-minute values, which are single 15-second averages.

An algorithm running in the BPR generates predicted water height values and compares all new samples with predicted values. If two 15-second water level values exceed the predicted values the system will go into the Tsunami Response Mode.

The data are then relayed via a satellite link to ground stations, which prepare the signals for immediate dissemination to the NOAA Tsunami Warning Centers, the NDBC and PMEL.

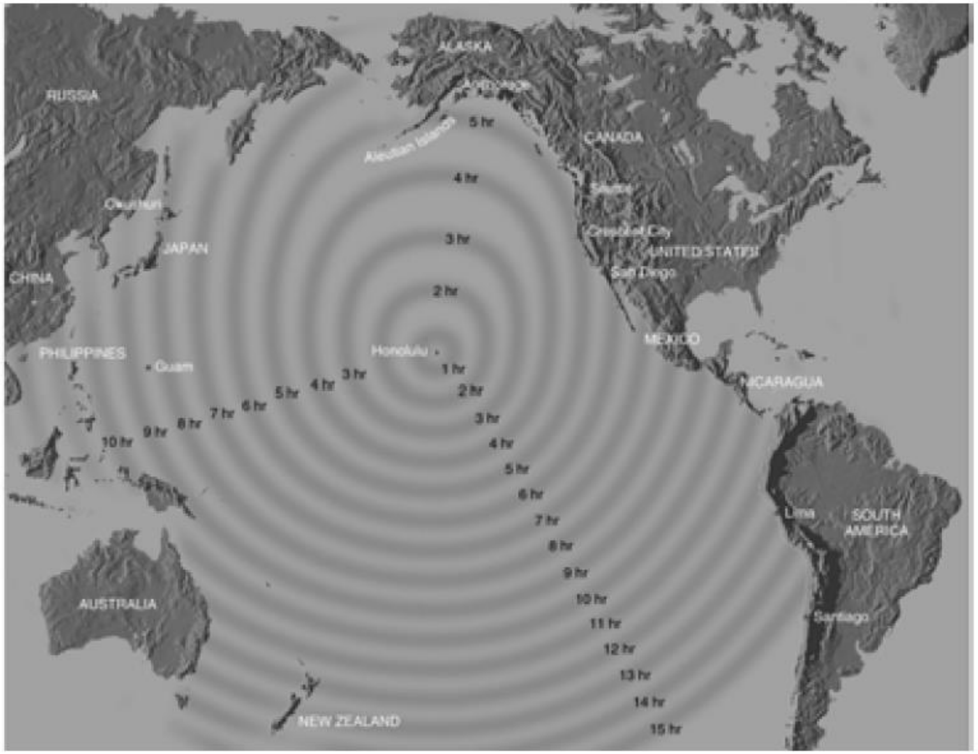
NOAA geophysicists use the data to determine the size of the wave, what areas may be at risk, and if a watch or warning is necessary. The DART research experience over the last 10 years indicates that these real-time systems are capable of detecting deep ocean tsunamis with amplitudes as small as one cm.

Current Meter Mooring



The velocity of tsunami currents can be measured using a current mooring which can give the current pattern of the water column triggered by the Tsunamis. Till now our nation don’t have dedicated current meter mooring that can provide valuable information about the current pattern and its characteristics in Indian Seas especially during extreme events like cyclones and tsunamis. It is proposed to install 10 nos. of current meter moorings.

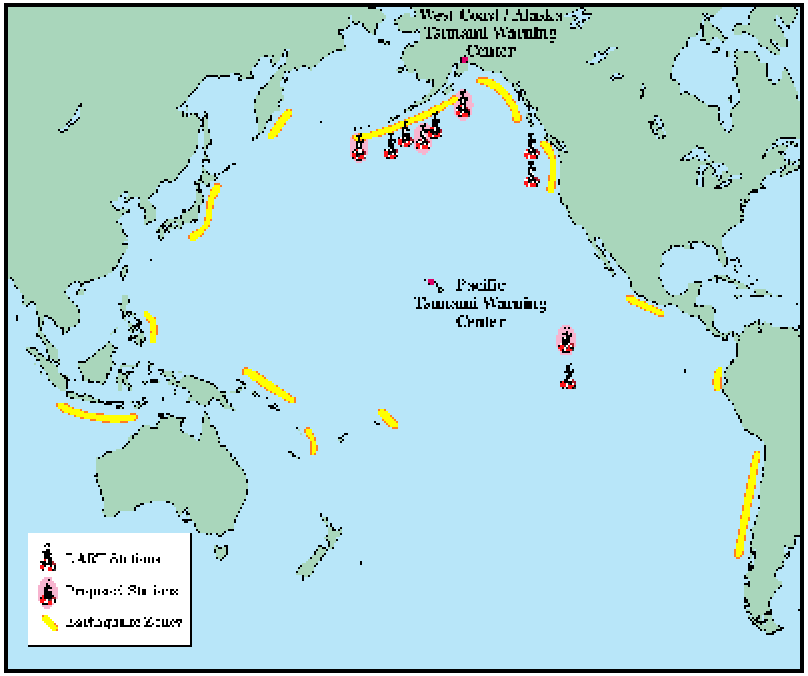
Tsunami Warning System



Times taken for tsunamis to reach Hawaii from certain locations

The tsunami warning system was established in 1946 following a devastating tsunami in Hawaii. Pacific Ocean-wide network of:-

- Seismic Station
- Tsunami Buoys
- Coastguards
- Civil defense

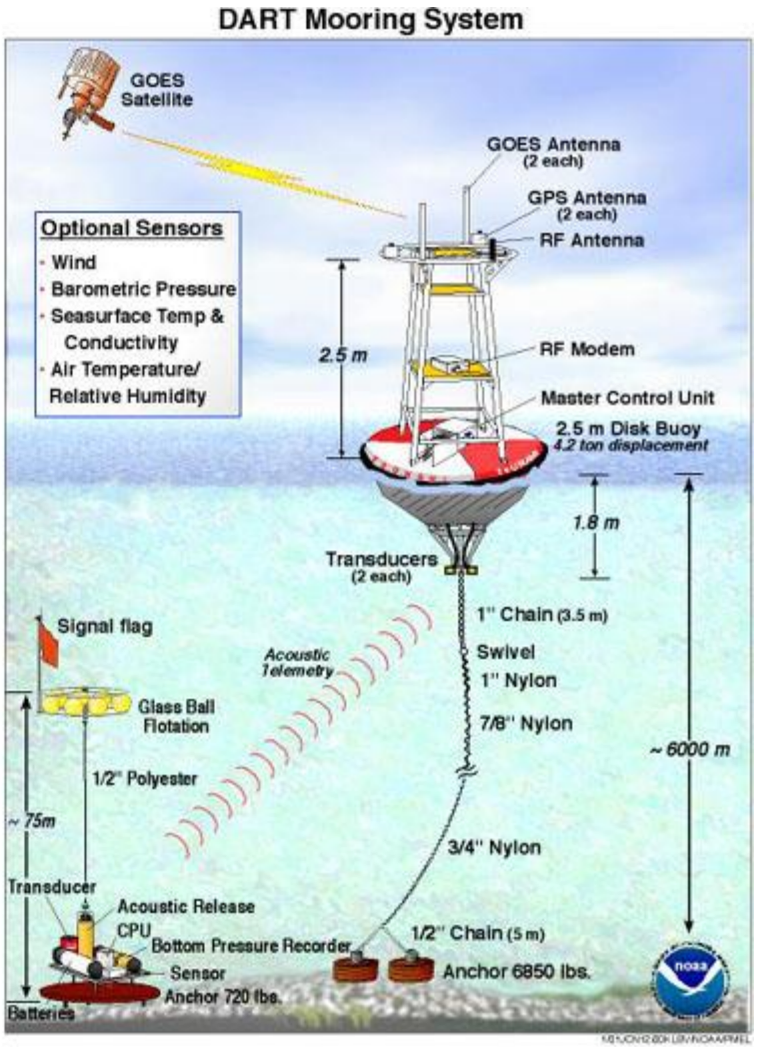


As part of the U.S.National Tsunami Hazard Mitigation Program (NTHMP), the DART Project is an ongoing effort to develop and implement a capability for the early detection and real-time reporting of tsunamis in the open ocean. DART is essential to fulfilling NOAA's national responsibility for tsunami hazard mitigation and warnings. Project goals are:

1) Reduce the loss of life and property in U.S. coastal communities.

2) Eliminate false alarms and the high economic cost of unnecessary evacuations.

DART stations are sited in regions with a history of generating destructive tsunamis to ensure early detection of tsunamis and to acquire data critical to real-time forecasts. Buoys shown on the accompanying map represent an operational array scheduled for completion in 2003.



A DART system consists of a seafloor bottom pressure recording (BPR) system capable of detecting tsunamis as small as 1 cm, and a moored surface buoy for real-time communications. An acoustic link is used to transmit data from the BPR on the seafloor to the surface buoy. The data are then relayed via a GOES satellite link to ground stations, which demodulate the signals for immediate dissemination to NOAA's Tsunami Warning Centers and PMEL.

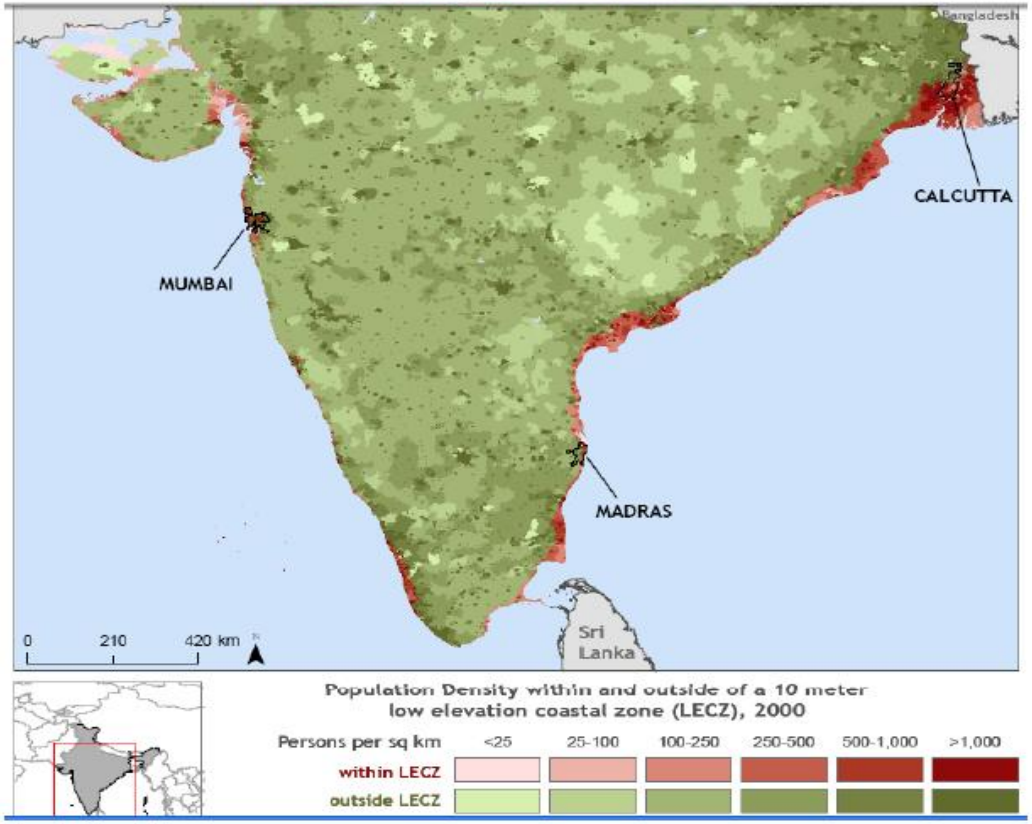
http://www.pmel.noaa.gov/tsunami/Dart/Flash/CODEframe4DART.html

TSUNAMI WARNING SYSTEM FOR INDIAN OCEAN

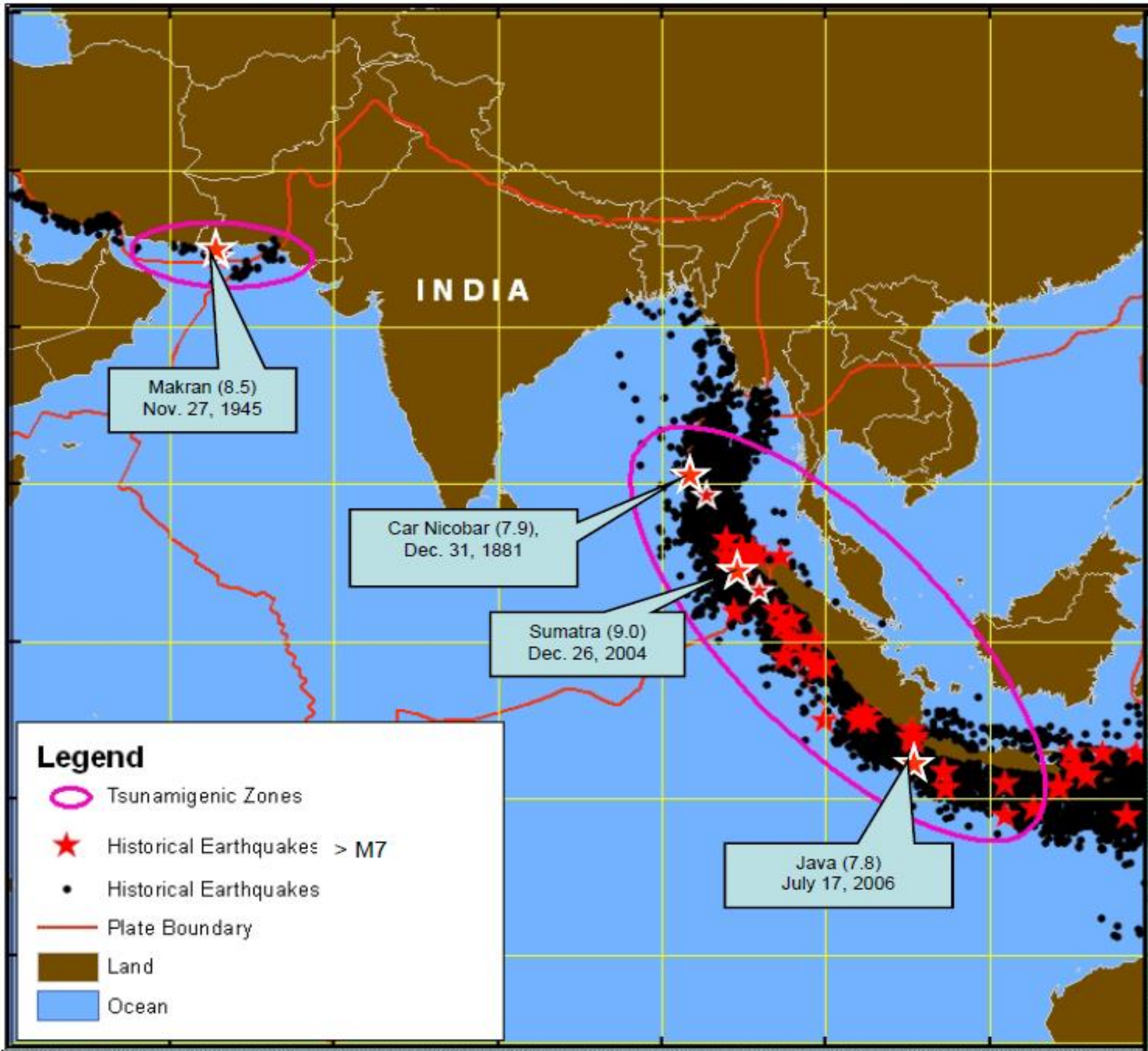
Vulnerability of the Indian Ocean Coastline

- More than 50 Nations around
- Many are Developing Countries
- More than1.5 Billion Population
- More than 66,500 km coastline

- 26 % of Indian Population live within 100 Km from the shoreline
- Most of the coastal areas are low lying and vulnerable to oceanogenic disasters such as Tsunamis, Storm Surges, Sea-level rise
- Dec 26, 2004 Tsunami resulted in a loss of 18, 045 deaths and 6,47,599 persons displaced



Risk Assessment - Historical Earthquakes & Tsunamis



Makran (8.5)
Nov. 27, 1945

Car Nicobar (7.9),
Dec. 31, 1881

Sumatra (9.0)
Dec. 26, 2004

Java (7.8)
July 17, 2006

Tsunamis are primarily caused due to large undersea Earthquakes.

For a tsunami to hit Indian coast, it is necessary that a tsunamigenic earthquake occurs and its magnitude should be larger than M 7. Possible locations of such events are enclosed in ellipse

Earthquakes with Slow Rupture Velocities are most efficient Tsunami Generators

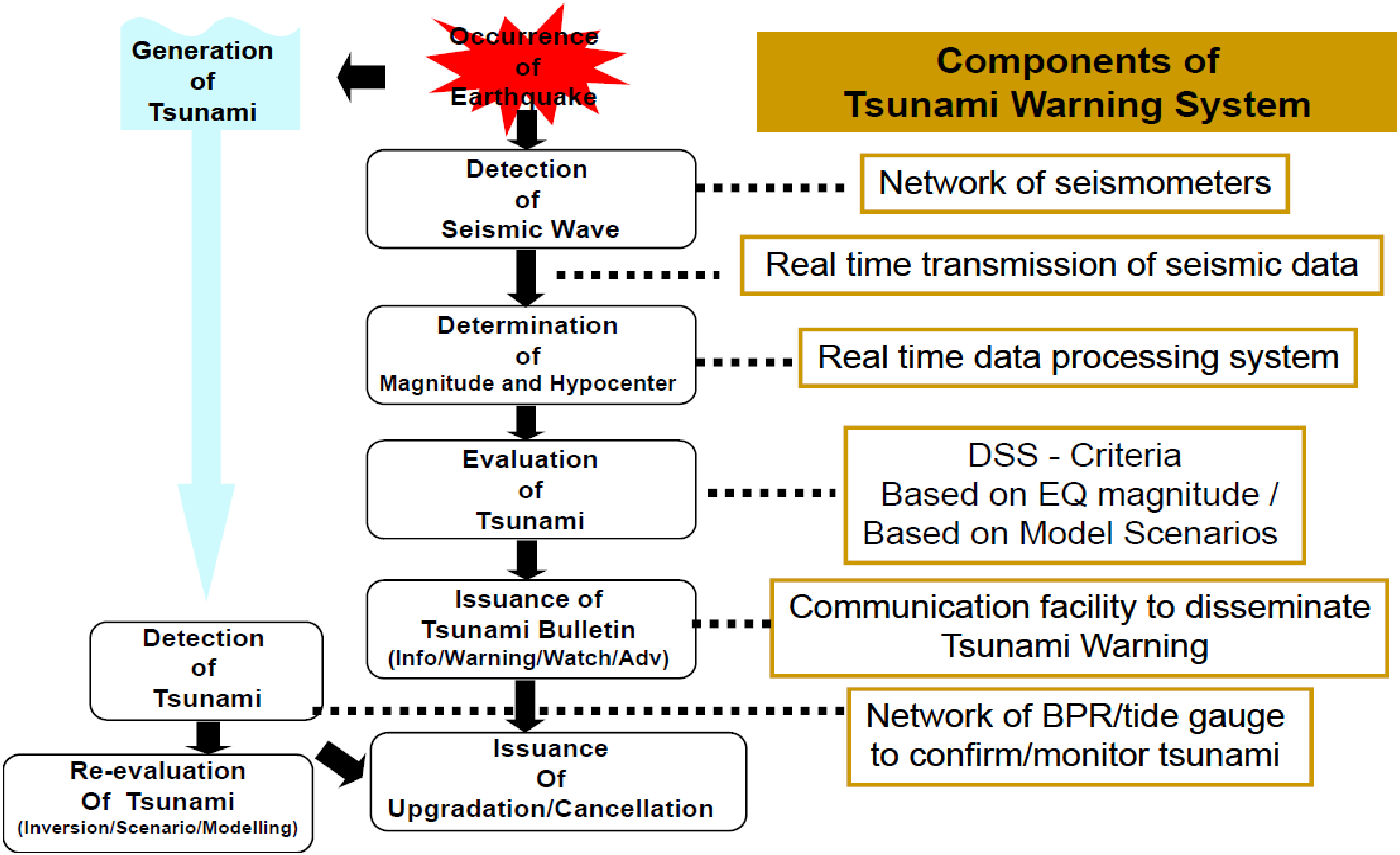
75% of earthquake energy is released in the circum-Pacific belt – 900 Tsunamis in 20th Century

20% in the Alpine-Himalayan belt – 6 Tsunamis in 20th Century

Historical Tsunami in India
12 Apr, 1762 (BoB EQ) – 1.8 M
31 Dec, 1881 (Car Nicobar EQ)
27 Aug, 1883 (Krakatoa) – 2 M
26 Jun, 1941 (Andaman EQ)
27 Nov, 1945 (Makran EQ) – 12 M
26 Dec, 2004 (Sumatra EQ)

Landslides, Volcanoes & Meteor Impacts can also generate Tsunamis

Sequence & Components of Tsunami Warning System



Generation of Tsunami

Occurrence of Earthquake

Detection of Seismic Wave

Determination of Magnitude and Hypocenter

Evaluation of Tsunami

Issuance of Tsunami Bulletin (Info/Warning/Watch/Adv)

Detection of Tsunami

Re-evaluation Of Tsunami (Inversion/Scenario/Modelling)

Issuance Of Upgradation/Cancellation

Components of Tsunami Warning System

Network of seismometers

Real time transmission of seismic data

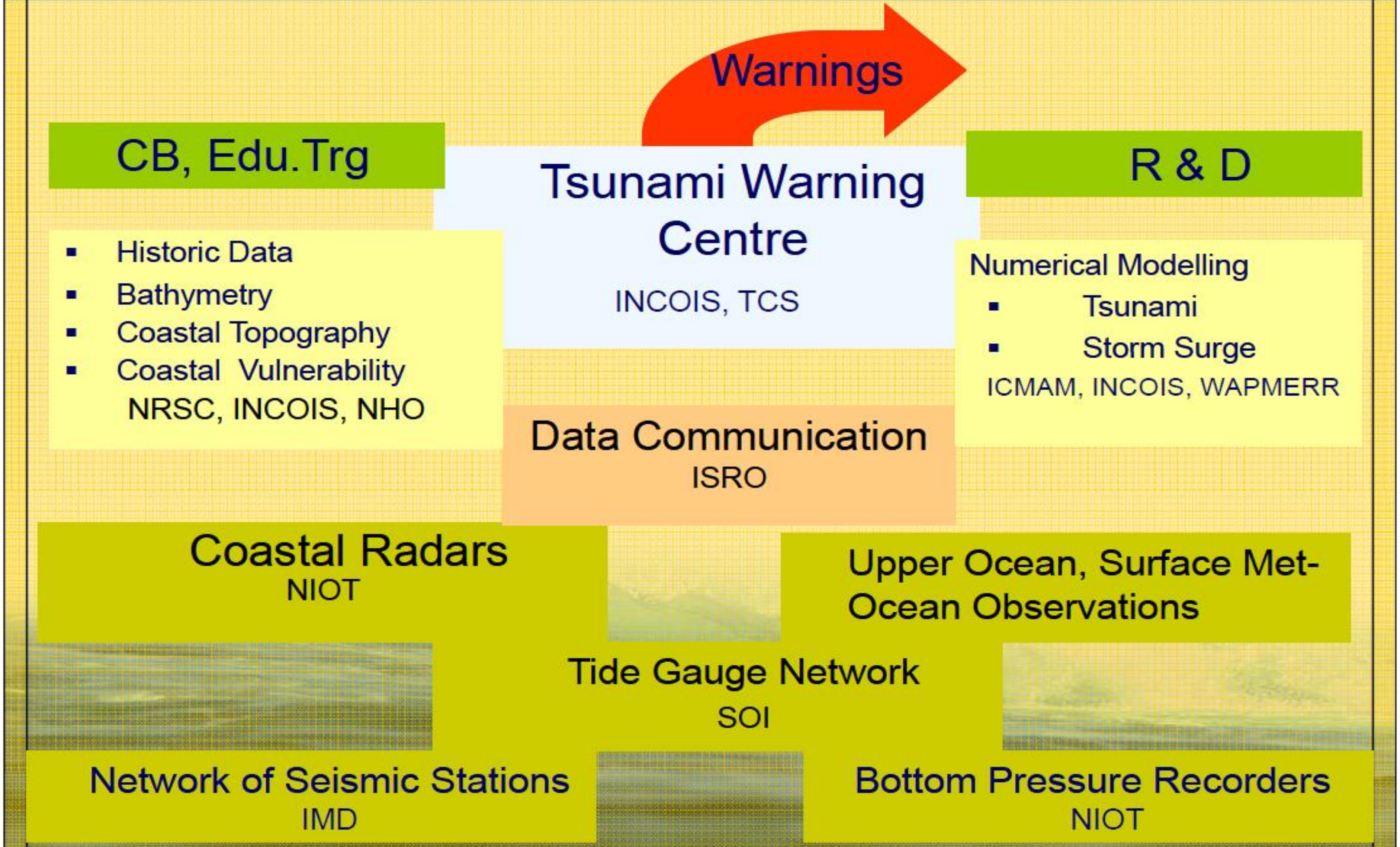
Real time data processing system

DSS - Criteria
Based on EQ magnitude /
Based on Model Scenarios

Communication facility to disseminate Tsunami Warning

Network of BPR/tide gauge to confirm/monitor tsunami

An end-to-end System Design



Warnings

CB, Edu.Trg

Tsunami Warning Centre

INCOIS, TCS

R & D

- Historic Data
- Bathymetry
- Coastal Topography
- Coastal Vulnerability

NRSC, INCOIS, NHO

Numerical Modelling

- Tsunami
- Storm Surge

ICMAM, INCOIS, WAPMERR

Data Communication

ISRO

Coastal Radars

NIOT

Upper Ocean, Surface Met-Ocean Observations

Tide Gauge Network

SOI

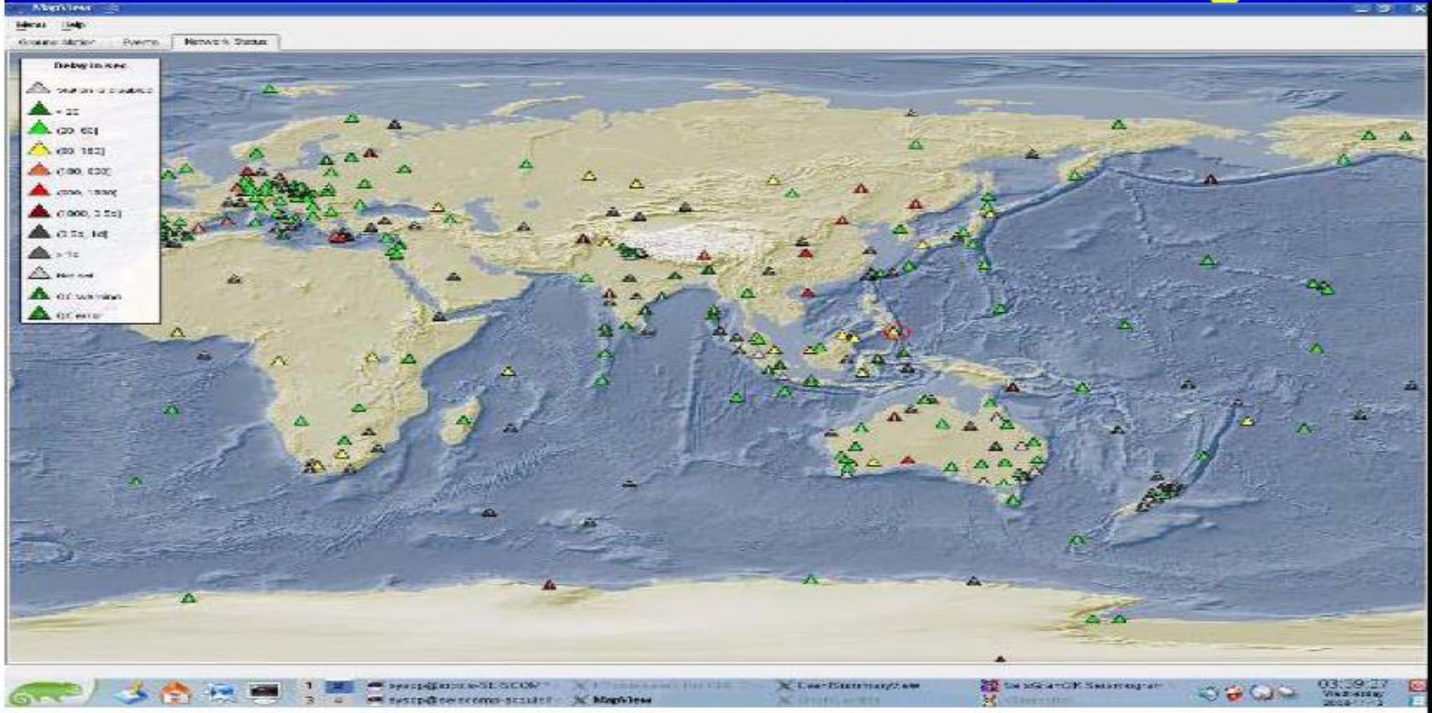
Network of Seismic Stations

IMD

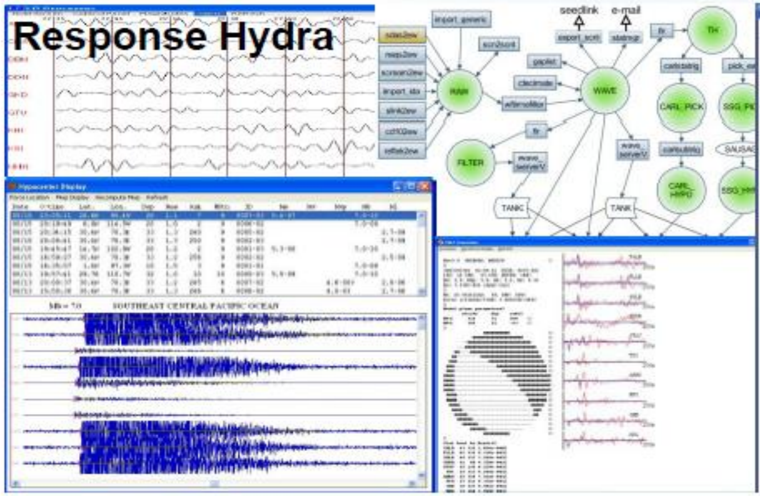
Bottom Pressure Recorders

NIOT

Real Time Seismic Monitoring Network



- Network of 27 Indian broadband seismic stations
- Data from International stations
- Data Acquisition, Processing, Auto location and Archival using Response Hydra as well as SESICOMP 3
- TWC reported and monitored 140 earthquakes of M > 6.0 (Jul 08 to July 09)
- 32 under-sea events of M > 6.5
- Earthquakes of > M6 are being auto-located within 5 - 12 Min of Occurrence
- EQ parameters conform well with those put out by USGS / GEOFON
- Upgrades to Seiscomp System - Mwp algorithm implemented



Response Hydra

Time

2007-05-03 11:03:17 UTC

7 minutes and 53 seconds ago

Region

Southern Sumatra, Indonesia

Magnitude

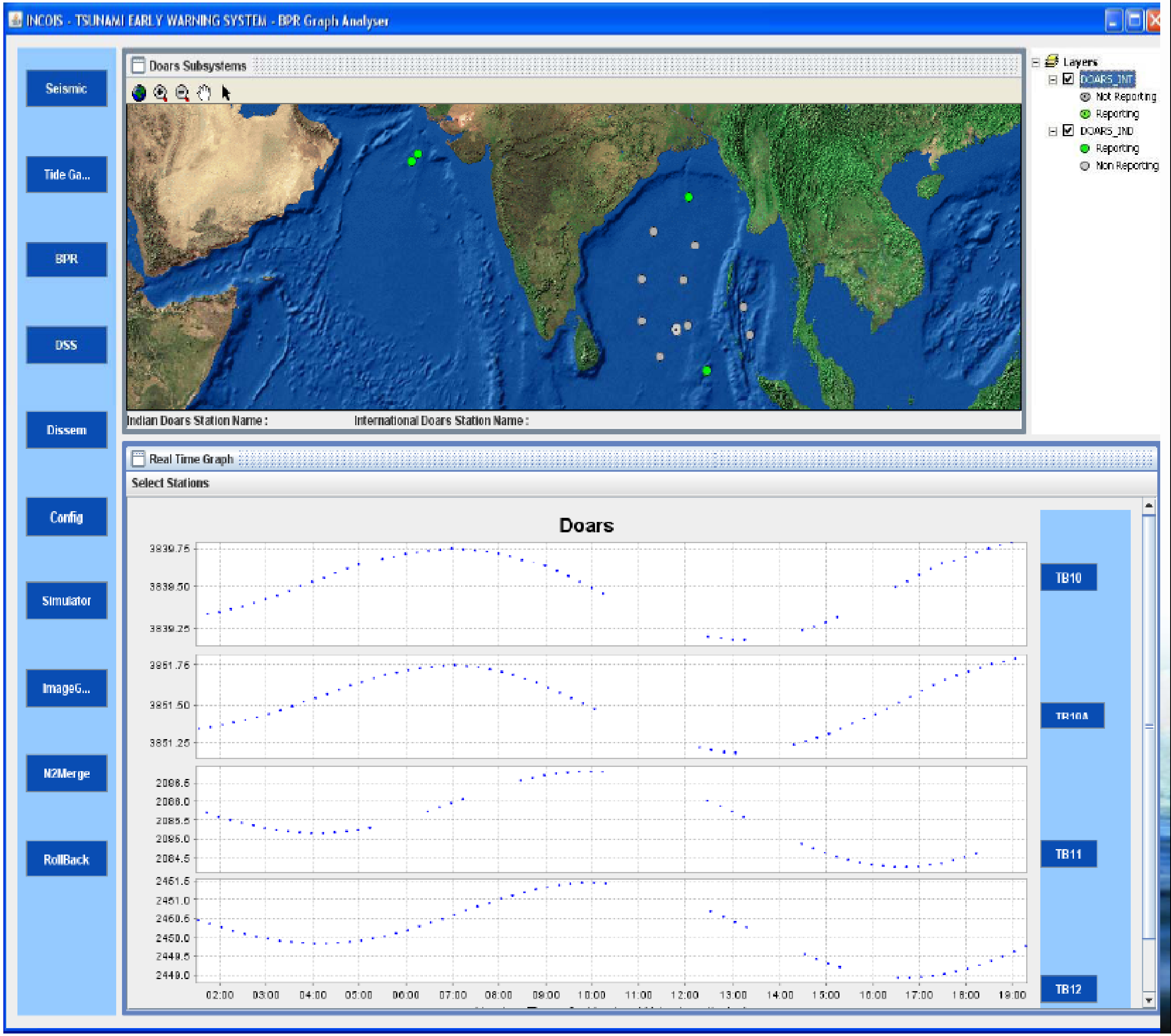
Mwp 6.6

Type	Value	+/-	Count
ML	6.6	0.31	18
Mwp	**6.6**	**0.14**	**45**
mB	6.9	0.36	17
mb	5.9	0.31	36

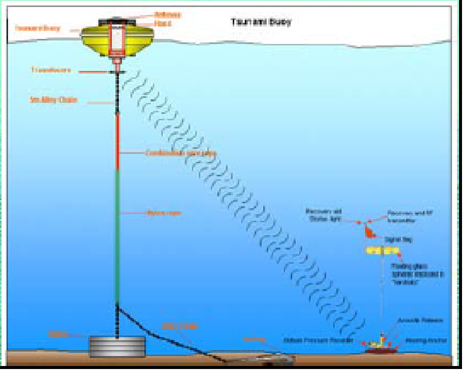
Hypocenter

Latitude:	0.48 ° S	+/- 2 km
Longitude:	100.38 ° E	+/- 3 km
Depth:	10 km	fixed
Phase Count:	61	
RMS Residual:	2.7 s	
Azimuthal Gap:	95 °	
Agency:	autoloc@st37	
Origin Status:	automatic	
First Location:	O.T. + 1m 54s	
This Location:	O.T. + 7m 47s	

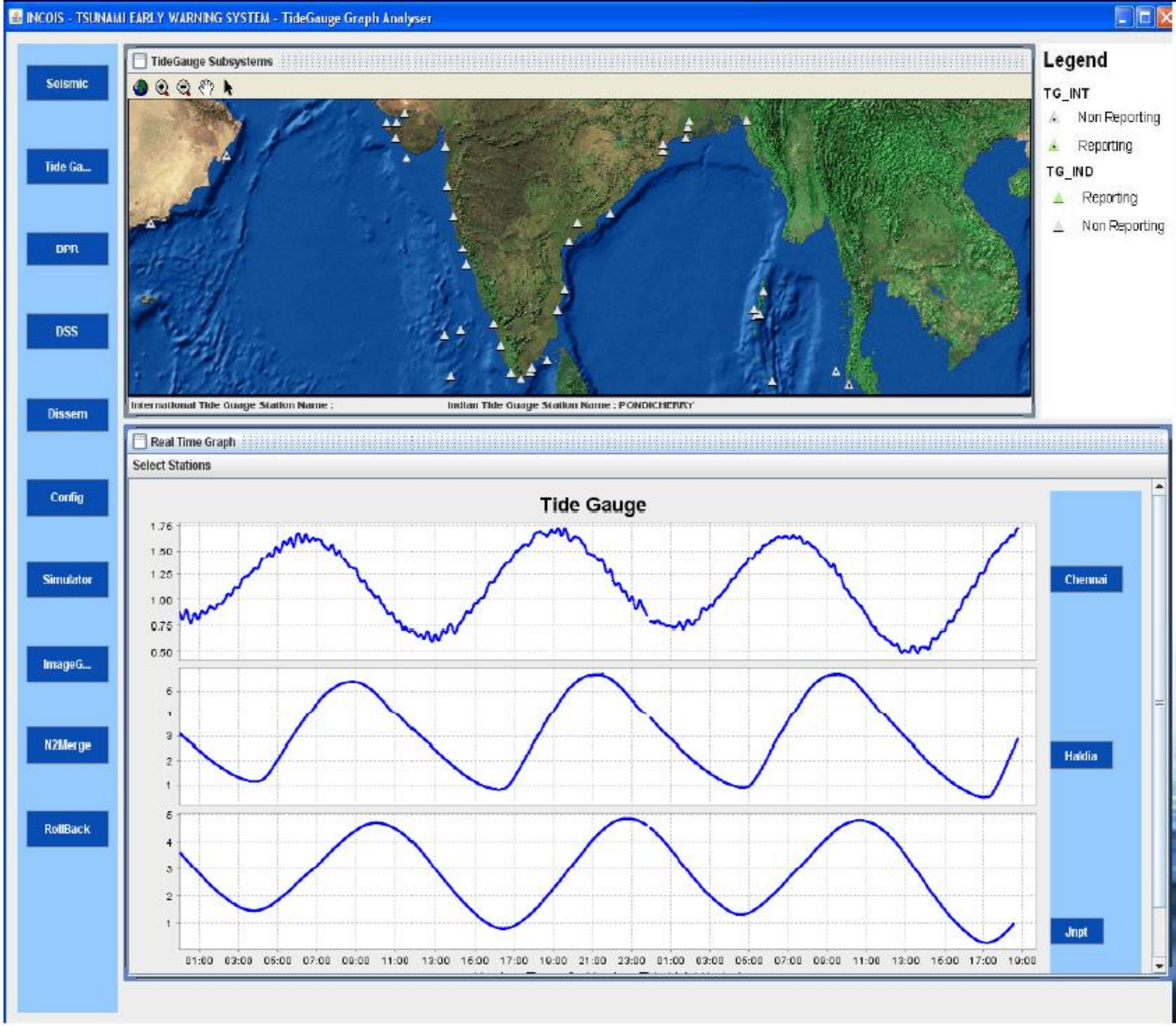
Deep Ocean Assessment and Reporting System for Detection of Tsunamis



- ➢ Network of 12 Tsunami Buoys are used to detect any significant water level changes due to tsunami
- ➢ Has a Bottom Pressure Recorder and a Surface Buoy System with Acoustic communication
- ➢ Capable of Measuring 1 cm water level change in 6000 m water column
- ➢ 4 values of 15 minutes average for every one hour in Normal Mode
- ➢ 4 values of 15 seconds average for every one minute in Tsunami Mode
- ➢ Automatic Tsunami Detection Algorithm in the BPR



Tide Gauge Network

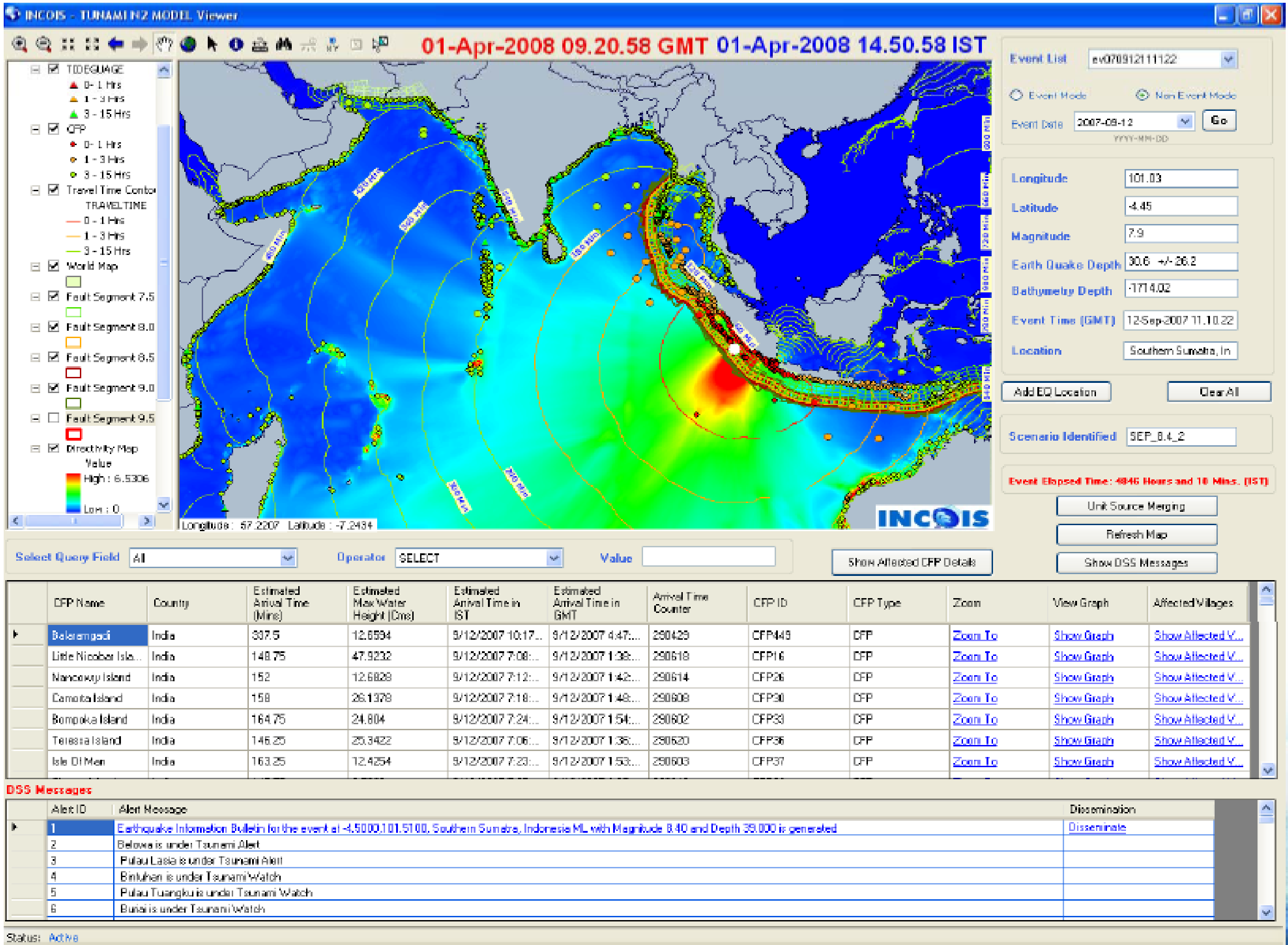


International Tide Guage Station Name :

Indian Tide Guage Station Name : PONDICHERRY

- Currently Tide Gauges installed and operational at 26 strategic locations along the Indian Coast
- More being planned in 12 locations in the next 1 year

Modelling for Operational Forecasting



INCOIS - TUNAMI N2 MODEL Viewer

01-Apr-2008 09.20.58 GMT 01-Apr-2008 14.50.58 IST

Longitude : 57.2207 Latitude : -7.2434

Event List: ev070912111122

○ Event Mode ● Non Event Mode

Event Date: 2007-09-12 (YYYY-MM-DD)

Longitude: 101.03

Latitude: -4.45

Magnitude: 7.9

Earth Quake Depth: 30.6 +/- 26.2

Bathymetry Depth: -1714.02

Event Time (GMT): 12-Sep-2007 11.10.22

Location: Southern Sumatra, In

Scenario Identified: SEP_8.4_2

Event Elapsed Time: 4846 Hours and 10 Mins. (IST)

Select Query Field: All Operator: SELECT Value:

CFP Name	Country	Estimated Arival Time (Mins)	Estimated Max Water Height (Cms)	Estimated Arival Time in IST	Estimated Arival Time in GMT	Arrival Time Counter	CFP ID	CFP Type	Zoom	View Graph	Affected Villages
Balaramgadi	India	337.5	12.6594	9/12/2007 10:17...	9/12/2007 4:47:...	290429	CFP449	CFP	Zoom To	Show Graph	Show Affected V...
Little Nicobar Isla...	India	148.75	47.9232	9/12/2007 7:08:...	9/12/2007 1:38:...	290618	CFP16	CFP	Zoom To	Show Graph	Show Affected V...
Nancowry Island	India	152	12.6828	9/12/2007 7:12:...	9/12/2007 1:42:...	290614	CFP26	CFP	Zoom To	Show Graph	Show Affected V...
Camorta Island	India	158	26.1378	9/12/2007 7:18:...	9/12/2007 1:48:...	290608	CFP30	CFP	Zoom To	Show Graph	Show Affected V...
Bompoka Island	India	164.75	24.804	9/12/2007 7:24:...	9/12/2007 1:54:...	290602	CFP33	CFP	Zoom To	Show Graph	Show Affected V...
Teressa Island	India	146.25	25.3422	9/12/2007 7:06:...	9/12/2007 1:36:...	290620	CFP36	CFP	Zoom To	Show Graph	Show Affected V...
Isle Of Man	India	163.25	12.4254	9/12/2007 7:23:...	9/12/2007 1:53:...	290603	CFP37	CFP	Zoom To	Show Graph	Show Affected V...

DSS Messages

Alert ID	Alert Message	Dissemination
1	Earthquake Information Bulletin for the event at -4.5000,101.5100, Southern Sumatra, Indonesia ML with Magnitude 8.40 and Depth 39.000 is generated	Disseminate
2	Belowa is under Tsunami Alert	
3	Pulau Lasia is under Tsunami Alert	
4	Binluhan is under Tsunami Watch	
5	Pulau Tuangku is under Tsunami Watch	
6	Buriai is under Tsunami Watch	

Status: Active

The TUNAMI N2 model is customized for Indian Ocean region

- ➢This model had been extensively validated using the December 26 2004 Tsunami observations

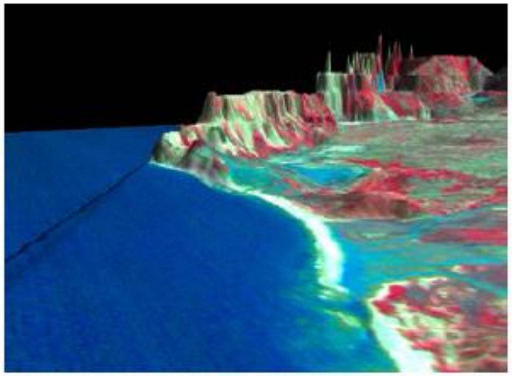
For operational forecast

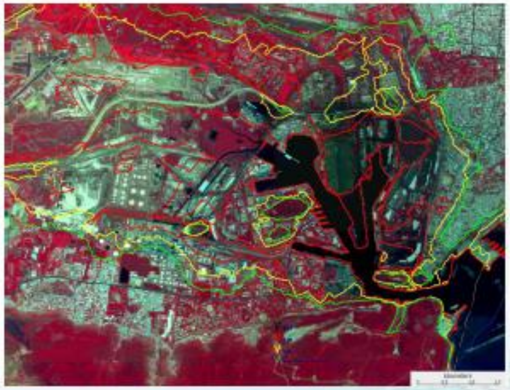
- ➢A large database of open ocean propagations scenarios
- ➢For epicenters separated by 100 km all along two Tsunamigenic zones
- ➢ Scenarios for different magnitudes (6.5, 7.0, 7.5, 8.0, 8.5, 9.0 & 9.5) and depths (10, 20, 40, 60, 80 & 100 km)

Travel times
Surge heights
Directivity maps

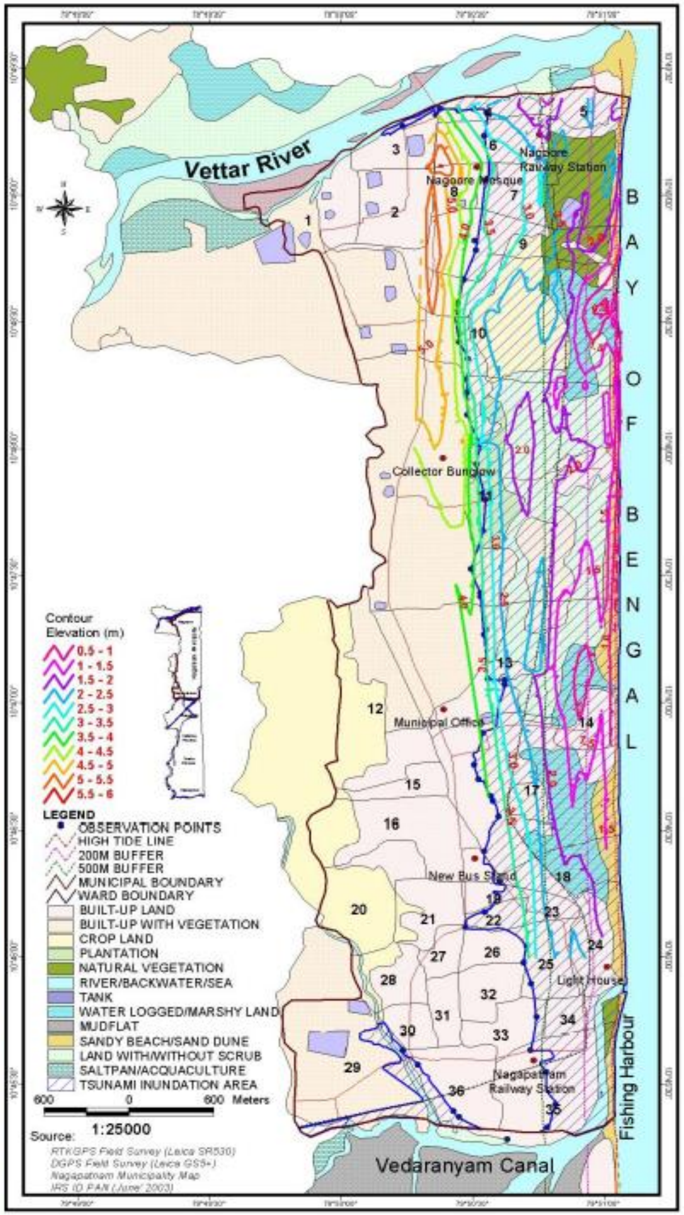
Each simulation covers the entire Indian Ocean domain with 15 hours simulation time and a time step of 5 seconds. Out put profiles are generated at 30 m bathymetry for about 1800 coastal fore cast points (CFPs) covering the entire Indian ocean rim countries

Coastal Topography, Bathymetry & Modelling





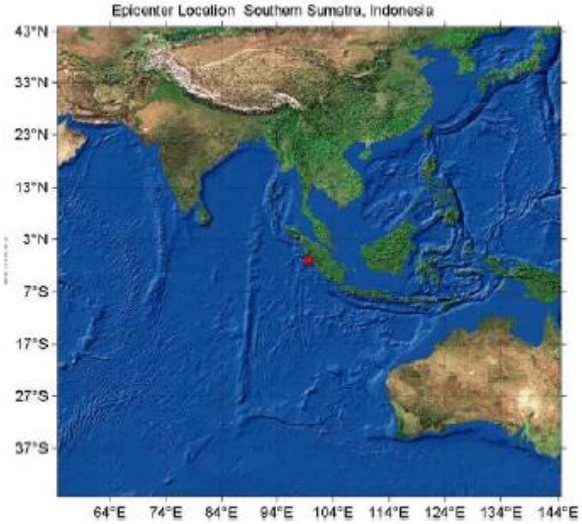
Bathymetric Survey for Cuddalore



Source:
RTKGPS Field Survey (Leica SR530)
DGPS Field Survey (Leica GS5+)
Nagapatnam Municipality Map
IRS ID PAN (June' 2003)

- Coastal Inundation scenarios simulated for 5 historical Earthquakes using TUNAMI N2 model and the predicted inundation areas have been overlaid on cadastral level maps of 1:5000 scale.
- Coastal Bathymetry: Maps of Special Order are required (Accuracy 0.5 M)
- Coastal Topography: Contour Intervals of 0.5 M at 1:25, 000 Scale are required
- Topography Data being generated using Cartosat and ALTM Surveys
- Bathymetric Survey conducted for a few vulnerable areas. Detailed survey being planned for other areas.

Handling of the Event by Warning Centers



Southern Sumatra Earthquake of M8.0 on 30th Sep 2009 at10:16:07 (UTC)

This earthquake generated a local tsunami near the epicenter especially at Padang, Indonesia (30 cm). The event did not generate any water level changes in Indian Coasts.

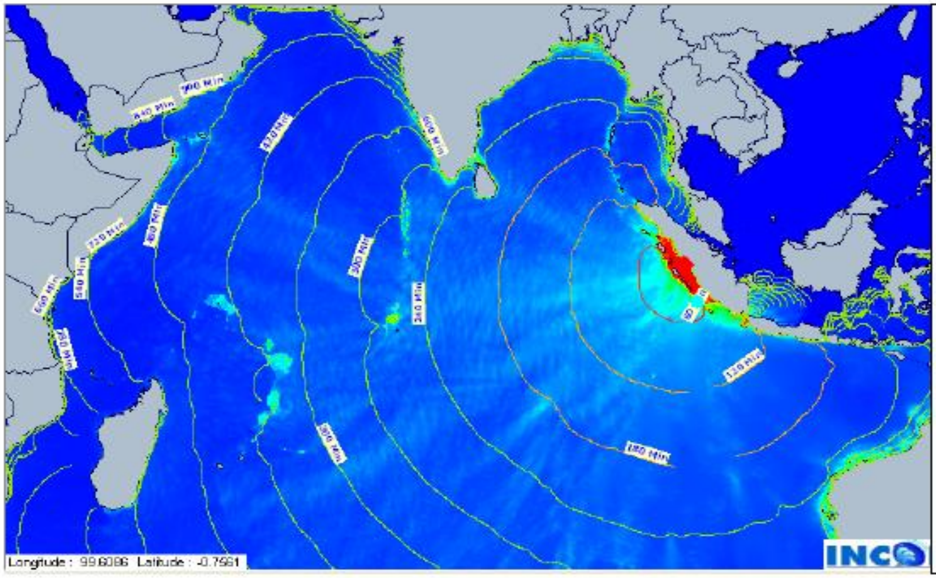
Different SOPs for the IO Region

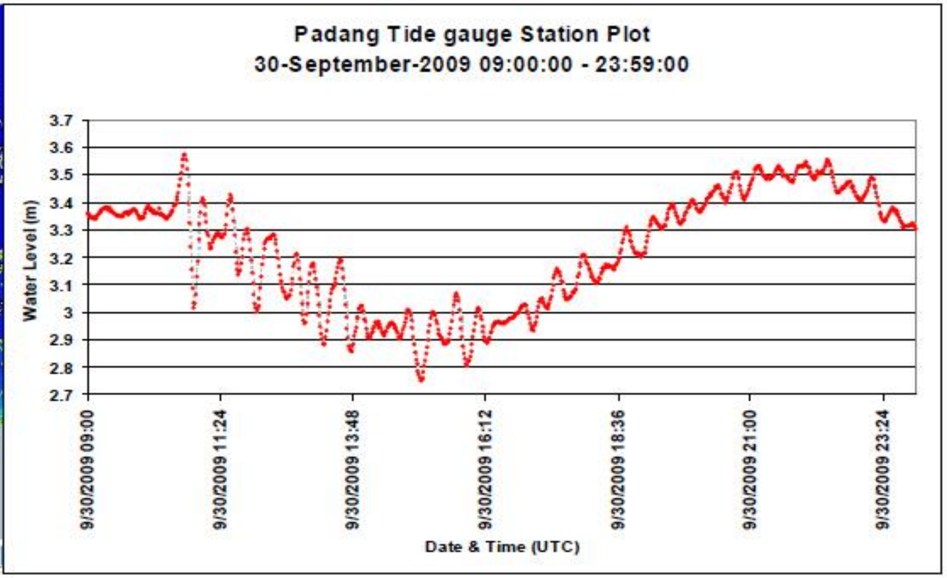
India: Eq info + Model Simulations + WL data

PTWC: Eq info + WL data

JMA: Eq info + WL data

Conflicting Bulletins





Significant role in the Indian Ocean

1. India-a key player major in the international coordination on arrangements for Indian Ocean region *[Kobe(Jan 05), Phuket (Jan 05), Paris (Mar 05), Mauritius (Apr 05) and Paris (Jun 05)]*
2. India is the only country that is developing capability to detect tsunami generated in the two tsunamigenic zones that would affect Indian Ocean
3. India served as Chairman of International Coordination Group set up by UNESCO/IOC for Indian Ocean Ocean Tsunami Warning and Mitigation System, a network of national systems
4. India is the First Country in the Indian Ocean to operationalise the TEWS that has been recognised as the most modern. ICG/IOTWS accepted Indias' offer to be Regional Tsunami Watch Provider for the Indian Ocean.

COASTAL EROSION

COASTAL HAZARDS

(i) Storm surges (half a dozen per year)

(ii) Tsunami (one to two every century)

(iii) Coastal pollution due to industrial and domestic effluents

(iv) Coastal erosion

(v) Oil spills

(vi) Harmful algal blooms

(vii) Submarine mudslides

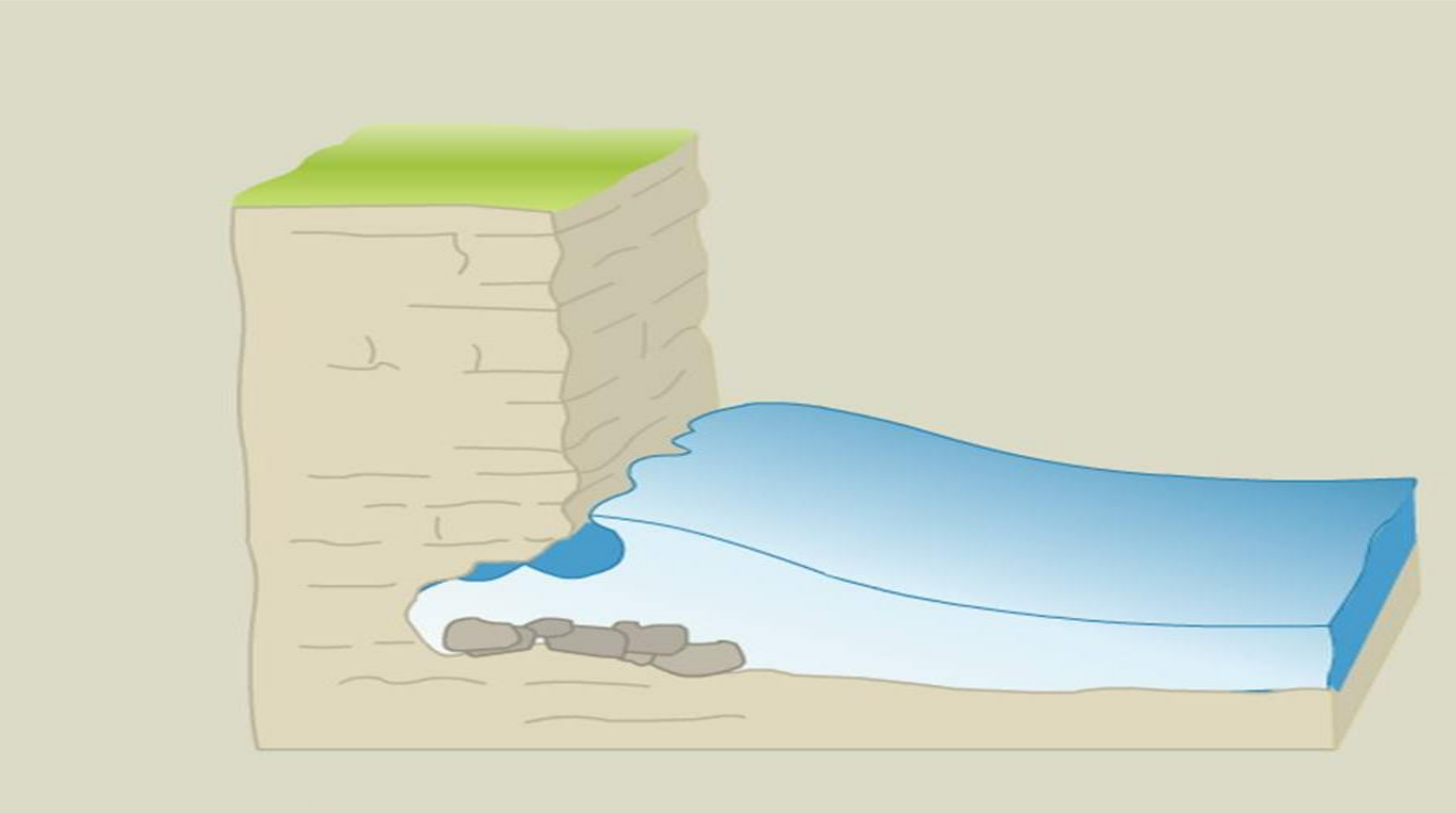
(viii) Hazards related to global climate change

COASTAL EROSION

- Coasts are subject to almost continuous change - either erode (retreat) or build seawards (accrete).

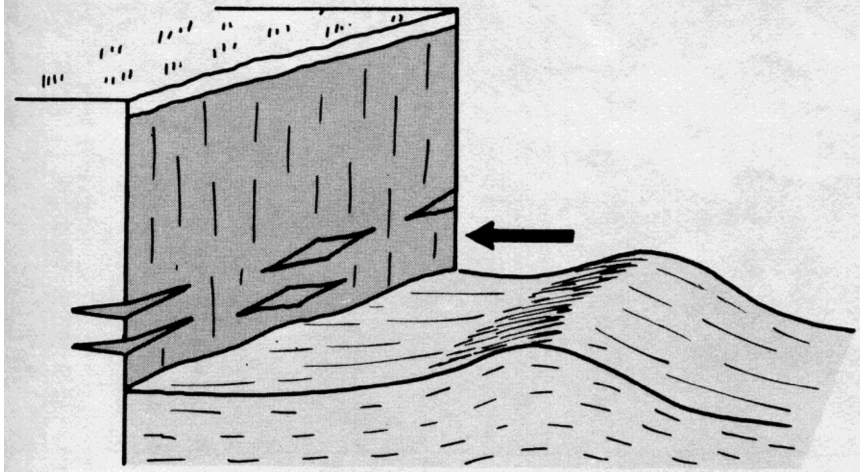
- Loss of subaerial landmass into a sea due to natural processes such as waves, winds and tides, or even due to human interference is called as coastal erosion.

There are four main forms of coastal erosion

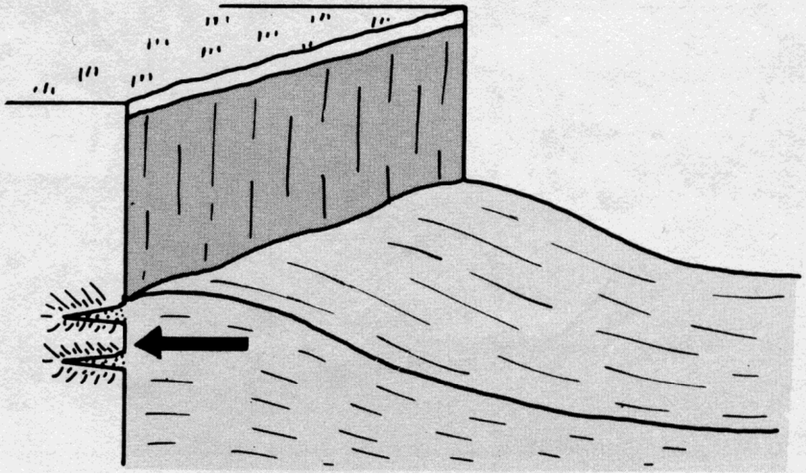


Hydraulic Action, Attrition, Abrasion, Solution

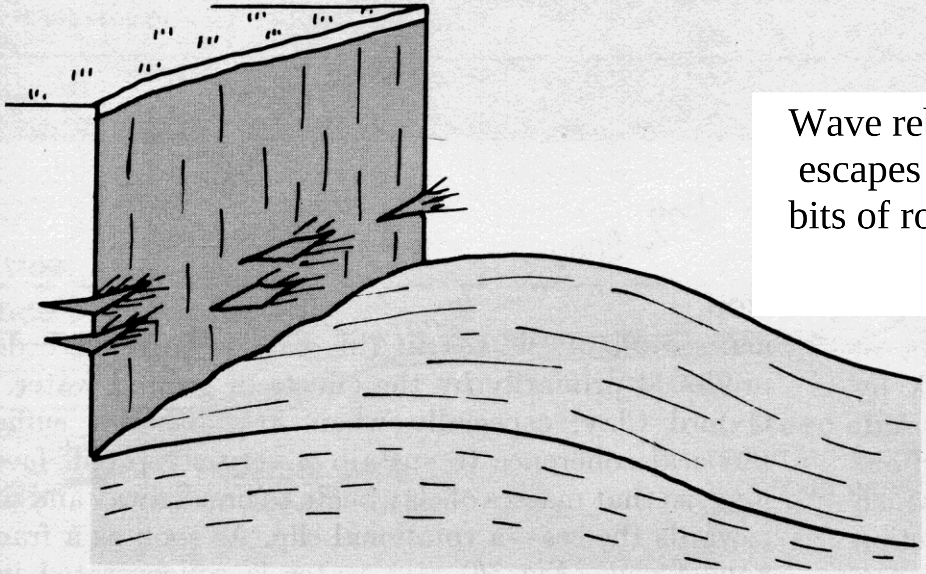
Hydraulic Action



Wave approaches the cliff. Note cracks exaggerated In size



Wave reaches the cliff & the air trapped by the wave is compressed into the crack.



Wave rebounds from the cliff & the compressed air escapes explosively, enlarging the cracks & ripping bits of rock off.

HYDRAULIC ACTION

Abrasion & Attrition (Corrasion)

Abrasion.

- The waves pick up the sediment & hurl it against the cliffs (uses the sediment as ammunition).

Attrition

- As the sediment is hurled against the cliff, bits are chipped off, the sediment gets smaller & rounder.
- Also as sediment roll against each other on a beach.

Corrosion (Solution)

- Salt & other chemicals in sea water attack & dissolve the cliffs.

Sub Aerial Processes

- The previous processes are caused by wave action & are called **CLIFF FOOT PROCESSES.**
- Sub Aerial processes are slope processes i.e weathering & mass movement, theses are called **CLIFF FACE PROCESSE**

EROSION IS CAUSED BY

- WAVES
- TIDAL STORMS
- NEAR SHORE CURRENTS
- OFFSHORE BANKS
- OFFSHORE BARS
- SAND SPIT
- TOMBOLO
- BAY
- MAN MADE STRUCTURES

TYPES OF EROSION

DUE TO WAVES

Water body obtains energy from wind, transfer across ocean and delivers
It to coastal zone

Collapse of wave near shoreline called as “wave break zone”

During winter waves will be high hence erosion more and summer less erosion

Summer swelling profile and winter storm profile to be taken into consideration

DUE TO TIDAL STORMS

Tides, low pressure and severe rainfall increase water level

Surf zone shifted towards land

Hence cause severe erosion well inside the land

Storm surges raise water level several meters accompanied by large waves cause severe erosion

DUE TO NEAR SHORE CURRENTS

Waves breaking parallel to the shore forms seaward flowing rip currents

Waves breaking at angles produce long shore currents parallel to the shore

DUE TO OFFSHORE BANKS

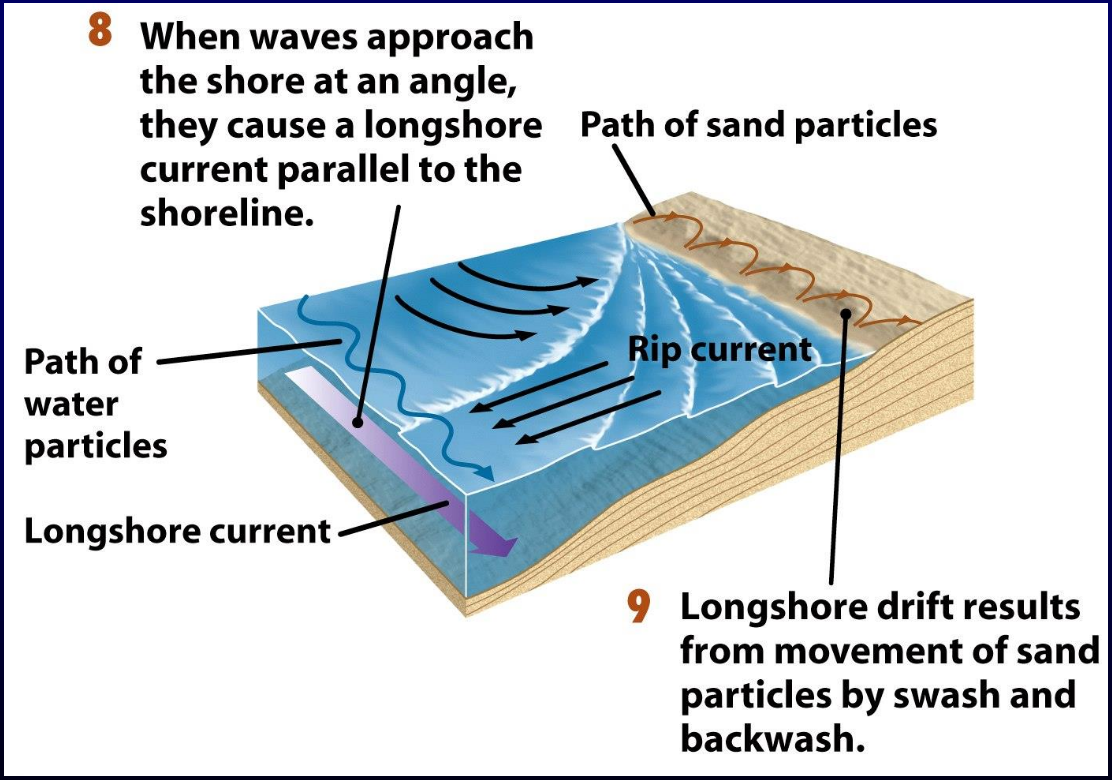
Change in the geometry of offshore banks (over period of 200 years) cause change in coastal morphology, areas once eroded show accretion and vice – versa

DUE TO OFFSHORE BARS

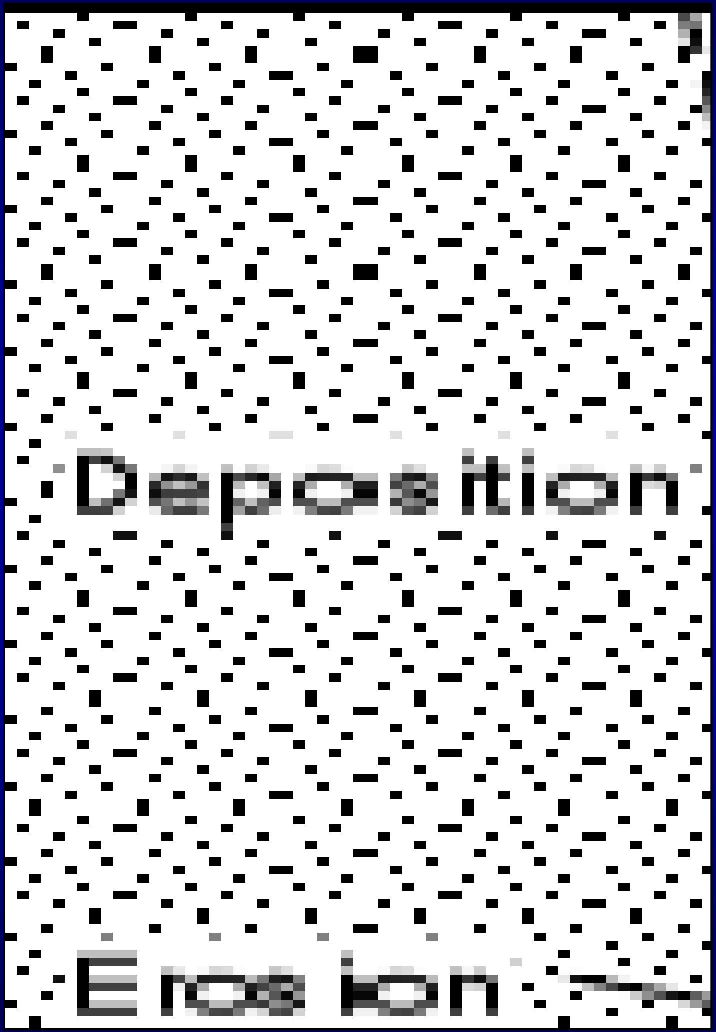
Normally found on river mouths, cause change in flow path of rivers causing Erosion on their banks

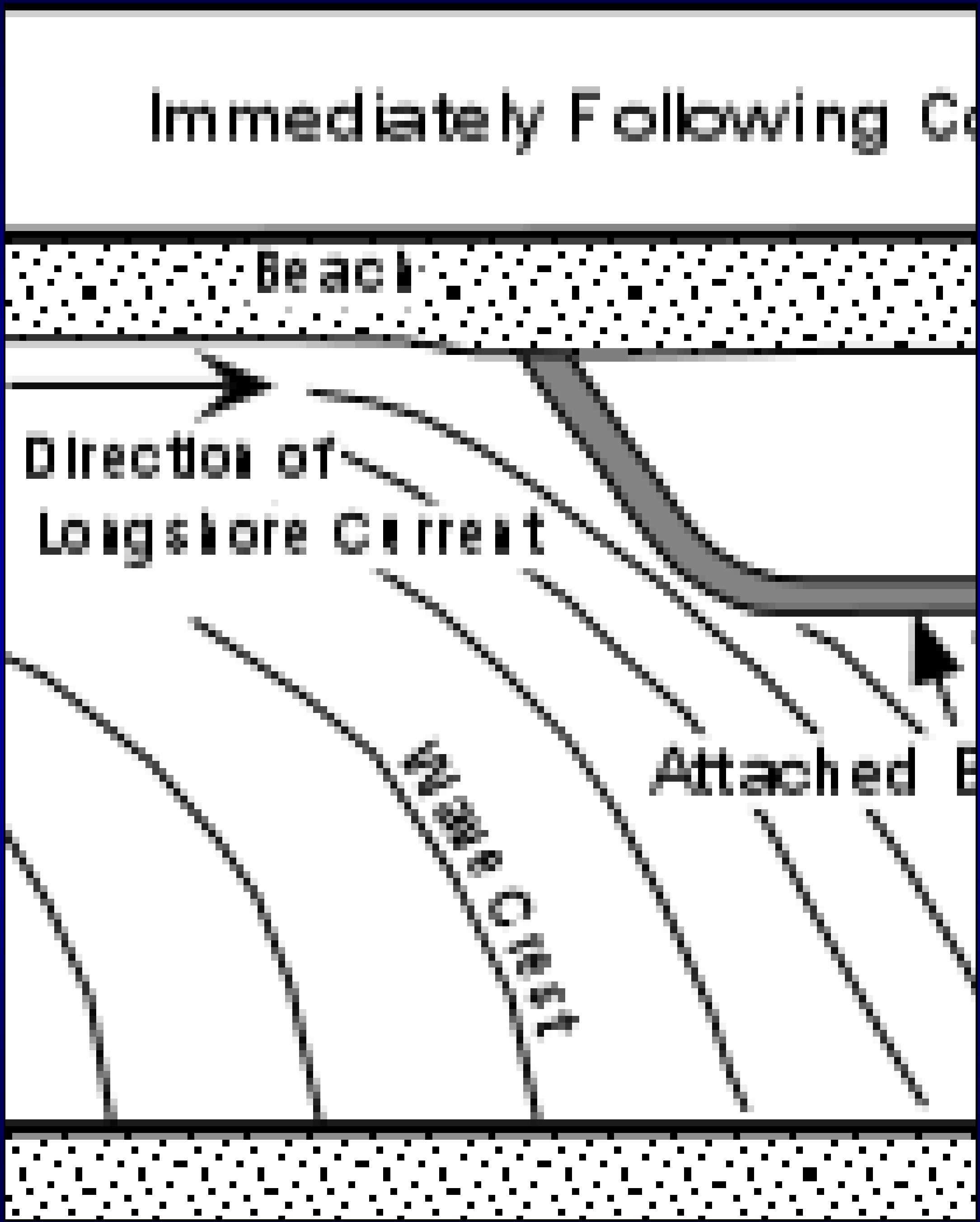
Rip currents

- ☛ When waves hit the coast and resolved into littoral currents and the seaward drifted currents such seaward drifted currents will be pushed back to the shore by wave
- ☛ This cause Rip currents



LONGSHORE CURRENTS





DUE TO SAND SPIT

Spit changes long shore currents causing accretion along spit and erosion in the updrift of the shoreline

Growth of spit cause severe erosion in the updrift

DUE TO TOMBOLO

Material that found attached between coastline and offshore

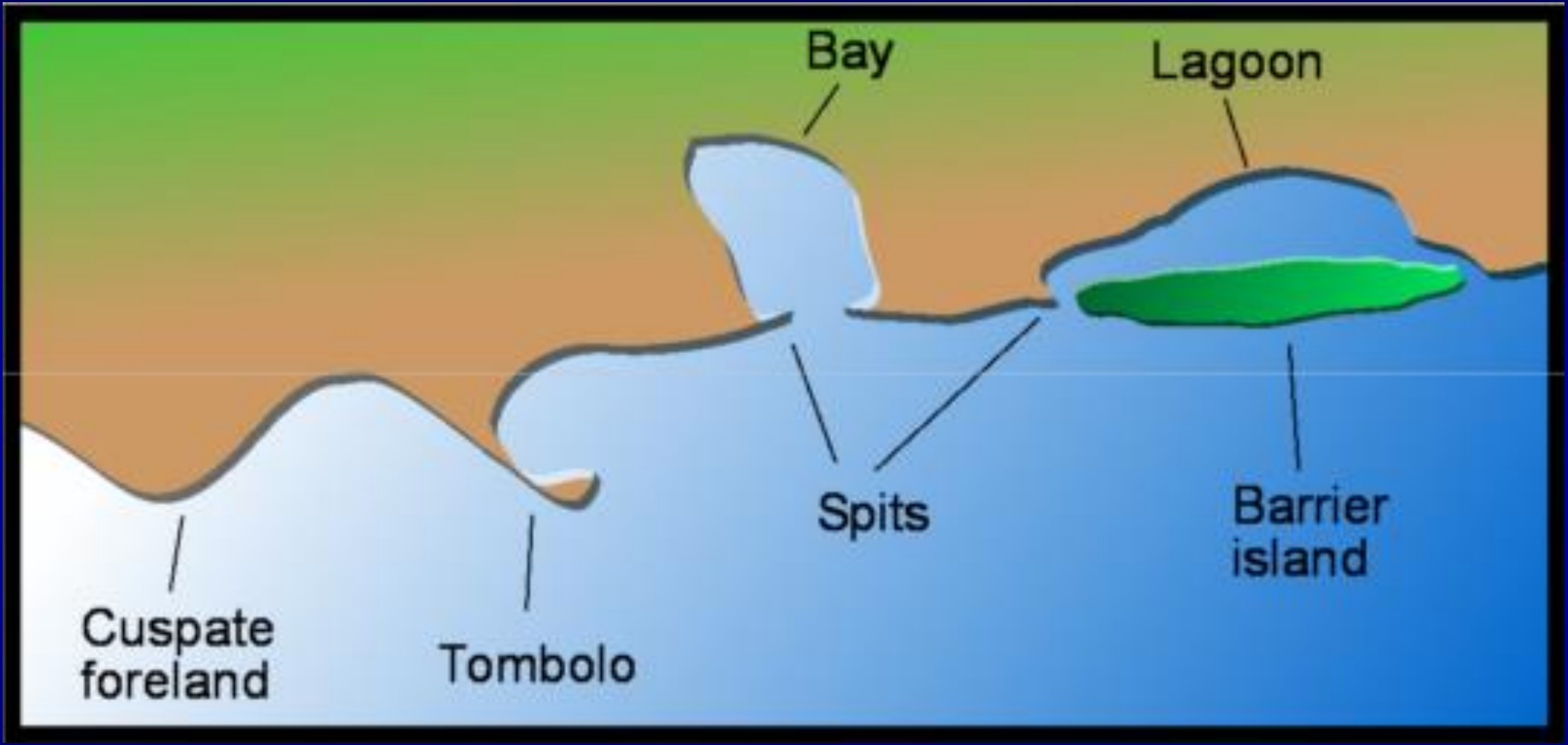
Cause littoral barriers leading to erosion in adjoining areas

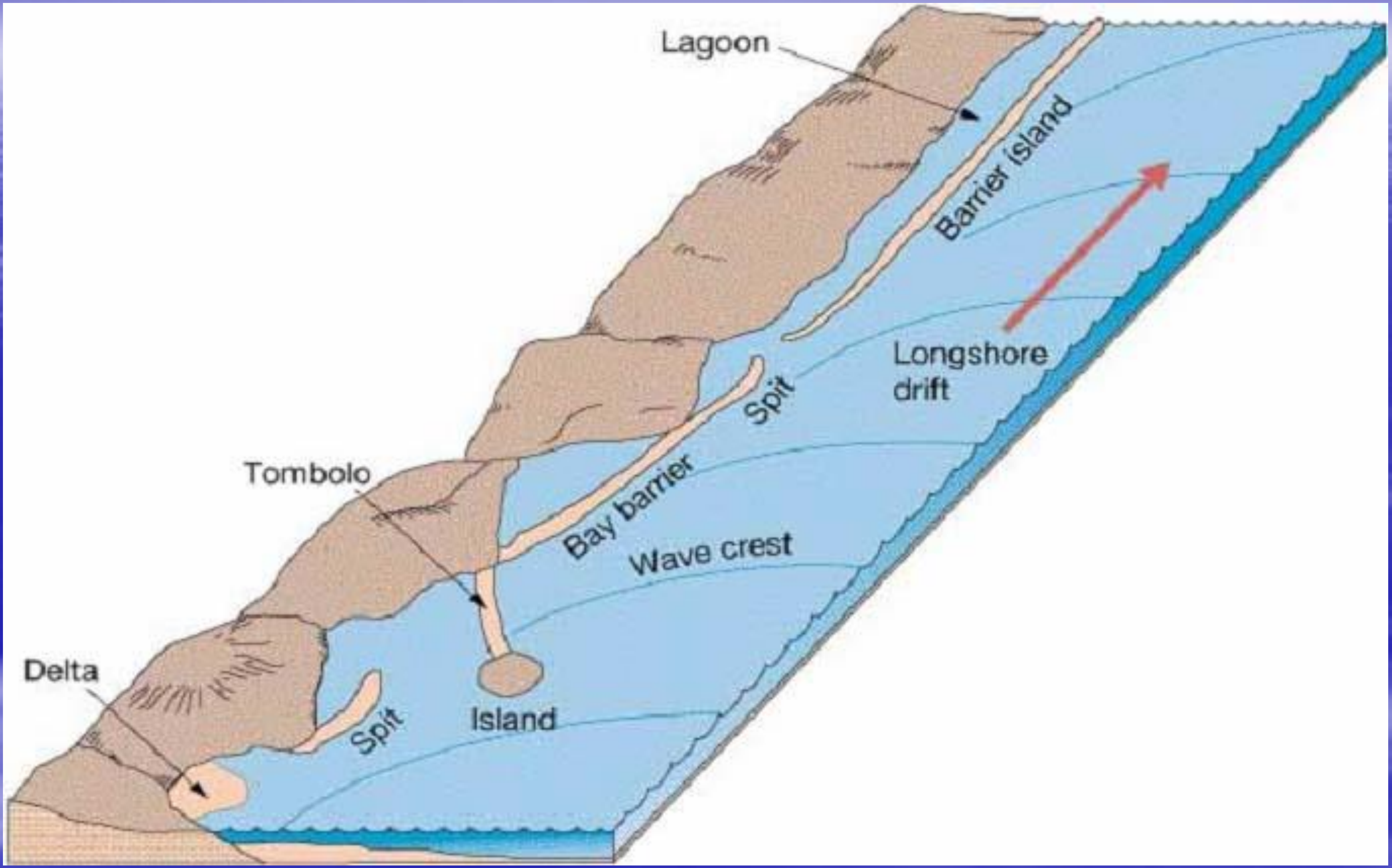
DUE TO BAY

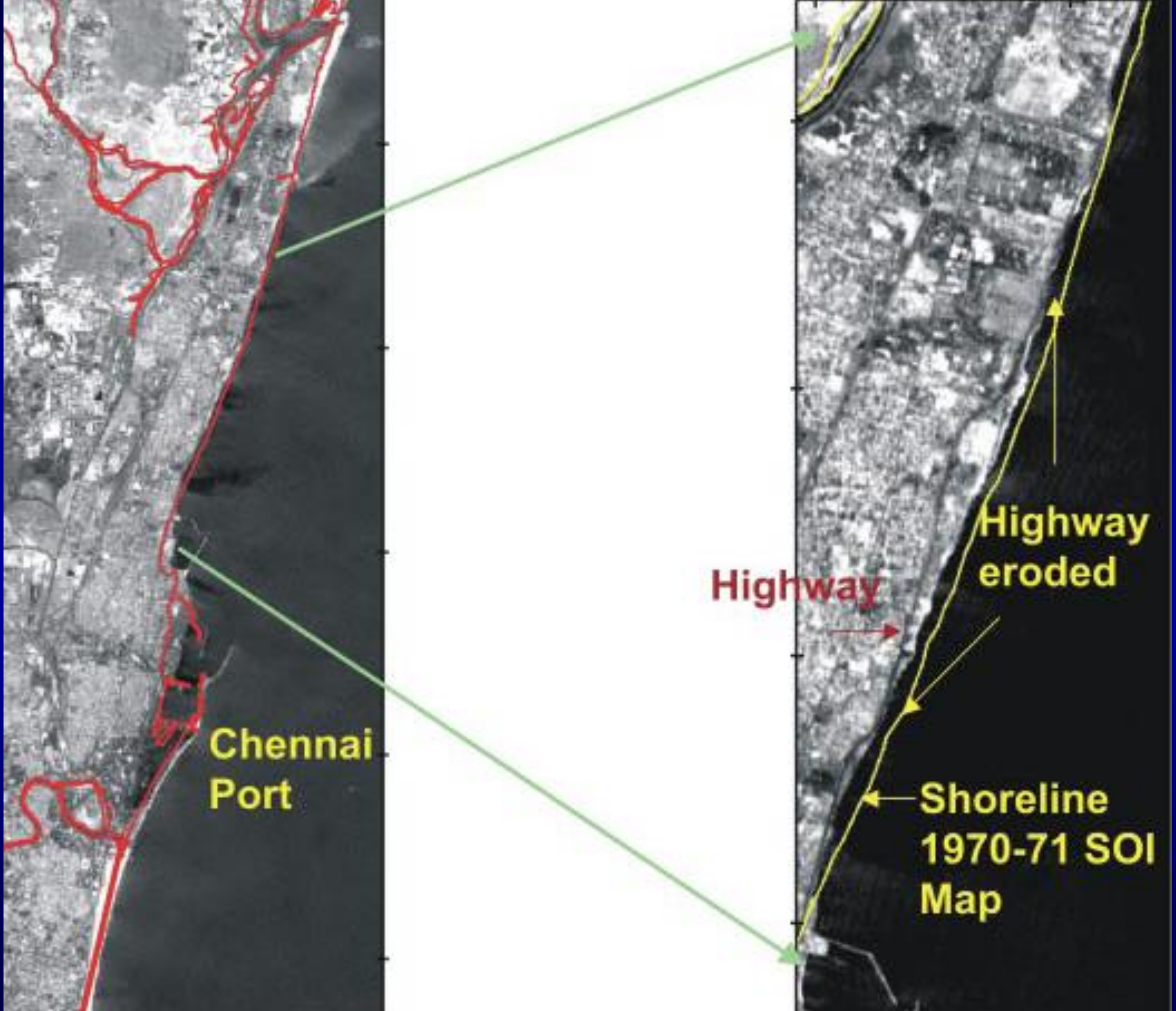
Change in wave direction cause movement of sediments within the bay

Hence accretion at one place and erosion in the other

Change in wave direction cause vice-versa effects


Bay
Lagoon
Spits
Barrier island
Cuspate foreland
Tombolo


Lagoon
Barrier island
Longshore drift
Spit
Tombolo
Bay barrier
Wave crest
Delta
Spit
Island

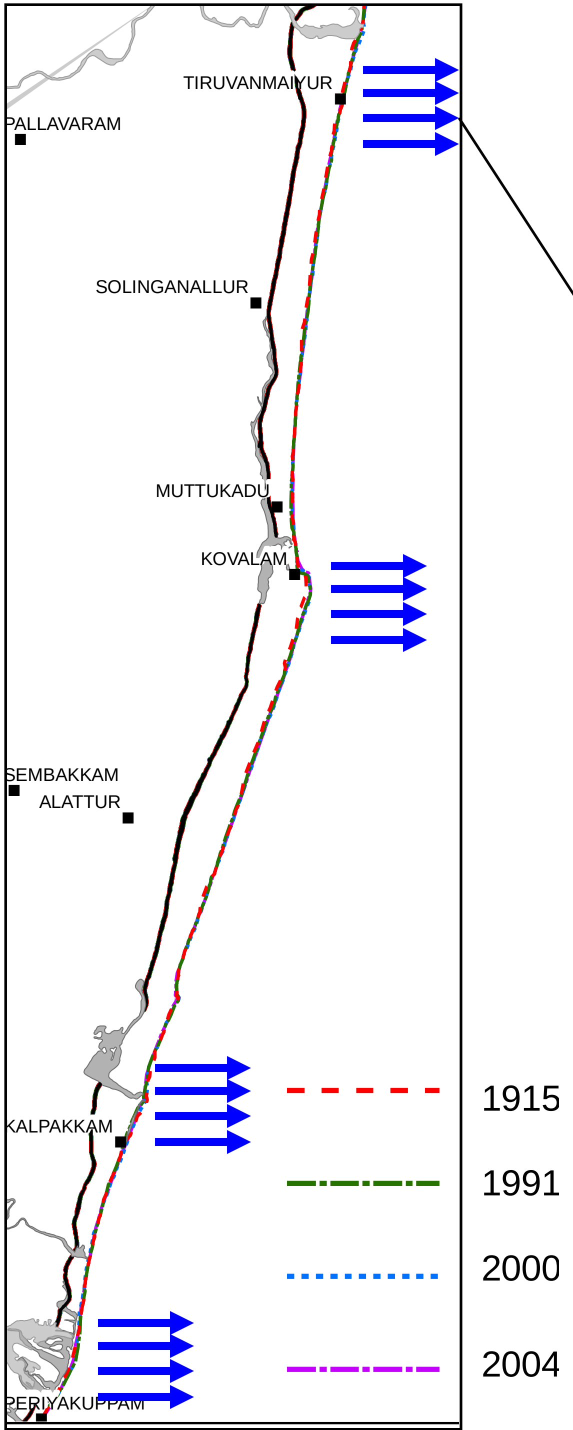

Chennai Port
Highway
Highway eroded
Shoreline 1970-71 SOI Map

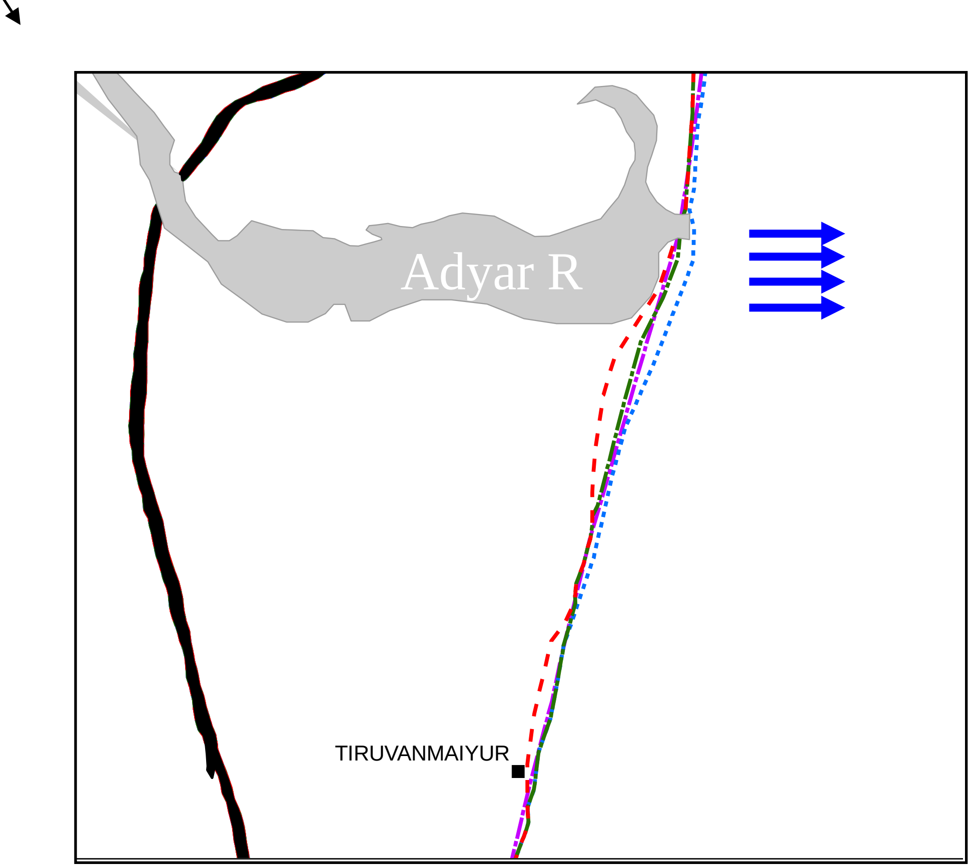
SHORELINE CHANGES

The shoreline during different periods were mapped using various data

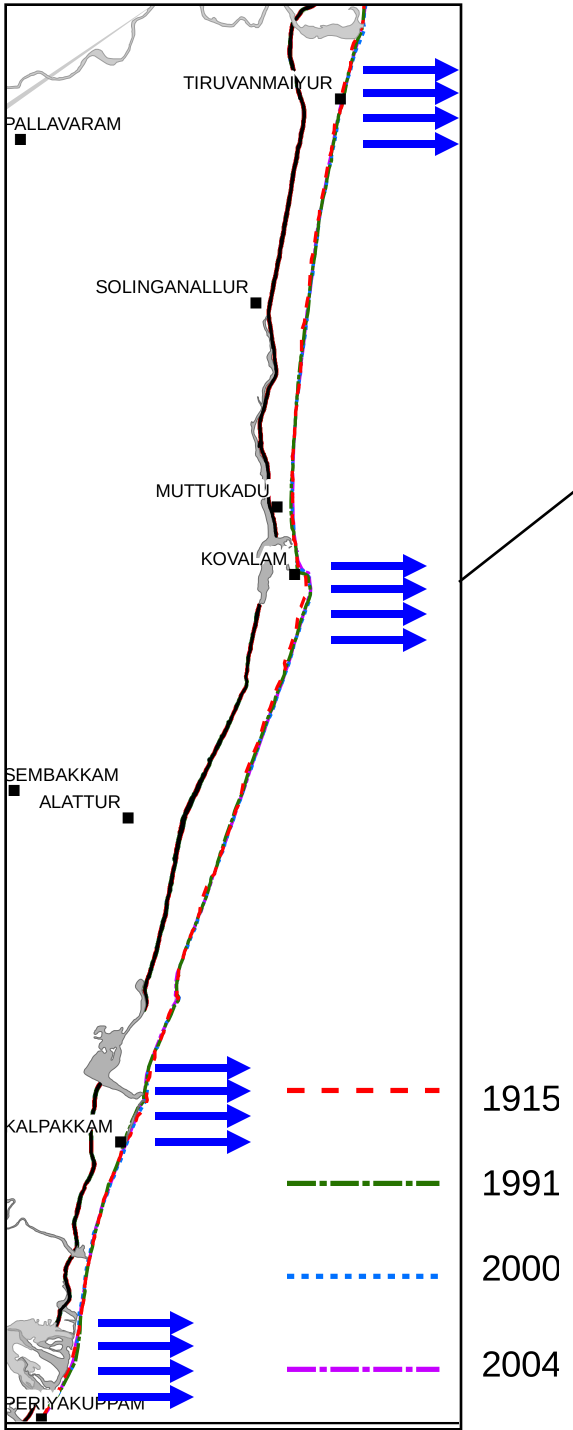
- **1915 – using old topographic sheets**
- **1991 – Using LANDSAT Thematic Mapper satellite data**
- **2000 – Using LANDSAT Enhanced Thematic Mapper data**
- **2004 – Using IRS P6 multi spectral data**

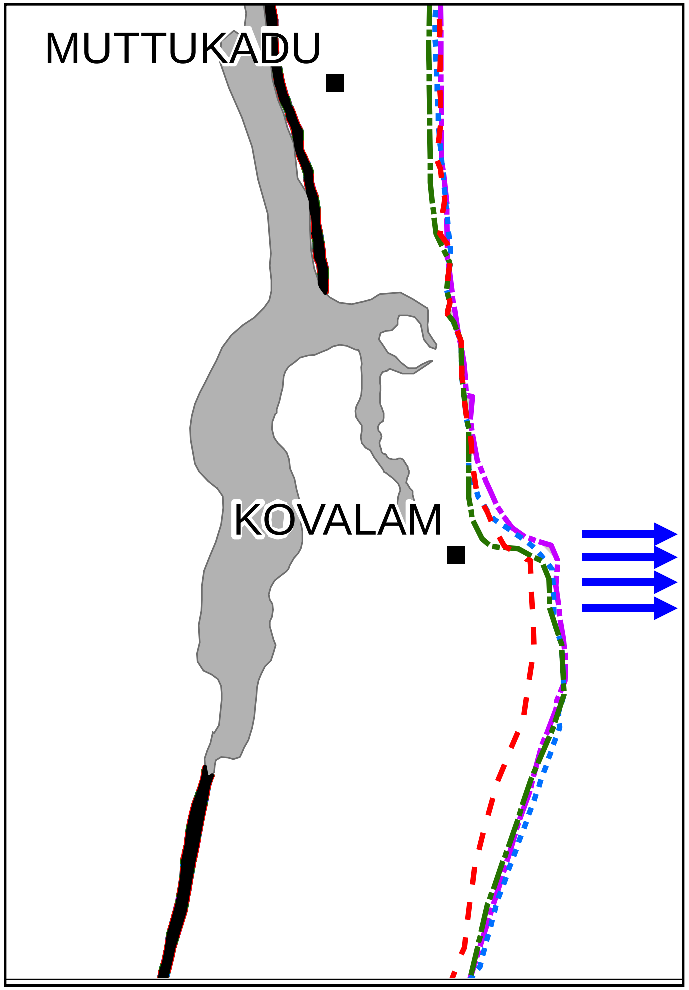
The land progradation at four areas, at Adyar river mouth, near Kovalam, Kalpakkam and Palar river mouth.



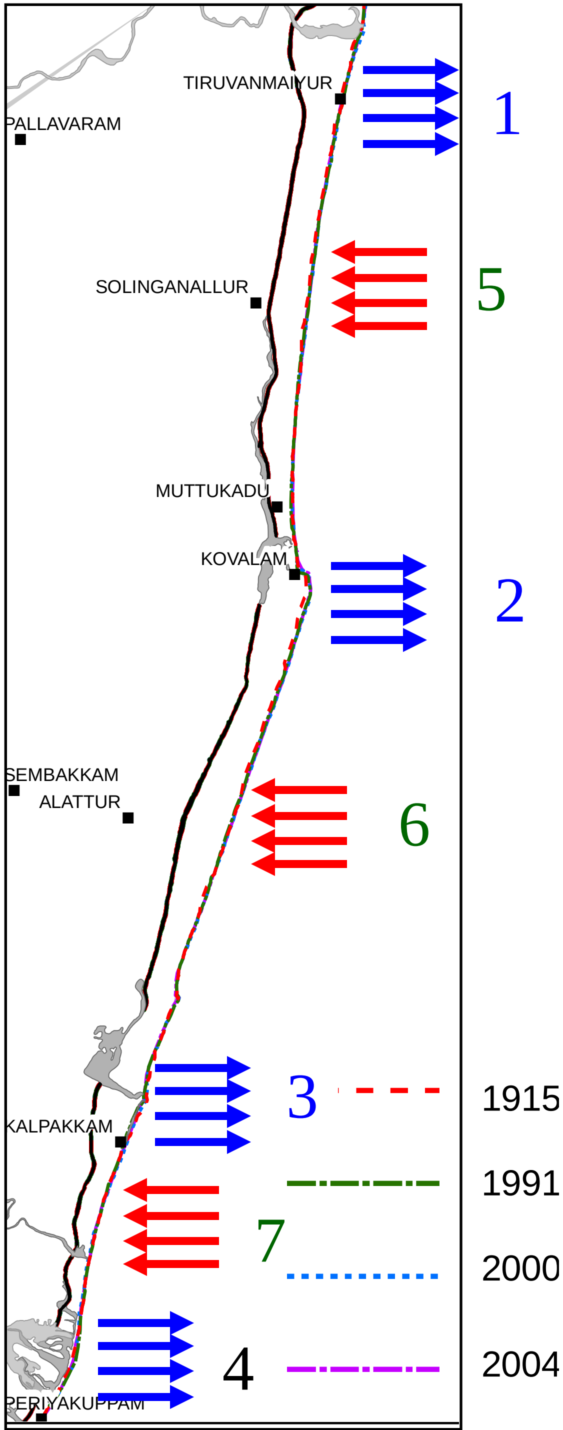


Land Progradation at Adyar R mouth





Land Progradation at Kovalam Creek mouth



The land progradation at four areas, at Adyar river mouth (1), near Kovalam (2), Kalpakkam (3) and Palar river mouth (4).

These four zones of land progradation were intervened by three zones of land loss at Solinganallur (5), Alattur (6) and north of Palar river mouth

PONDICHERRY - 1984

PONDICHERRY - 2000

EROSION DUE TO TSUNAMI NEAR NAGPATTINAM

Storm damage along the Mississippi coast from Hurricane Katrina, August 2005

DUE TO MAN MADE STRUCTURES

Harbors are developed by constructing wave breakers to form an enclosure of water body free from wave disturbance

Constructing jetties to prevent from long shore currents

MADRAS HARBOR

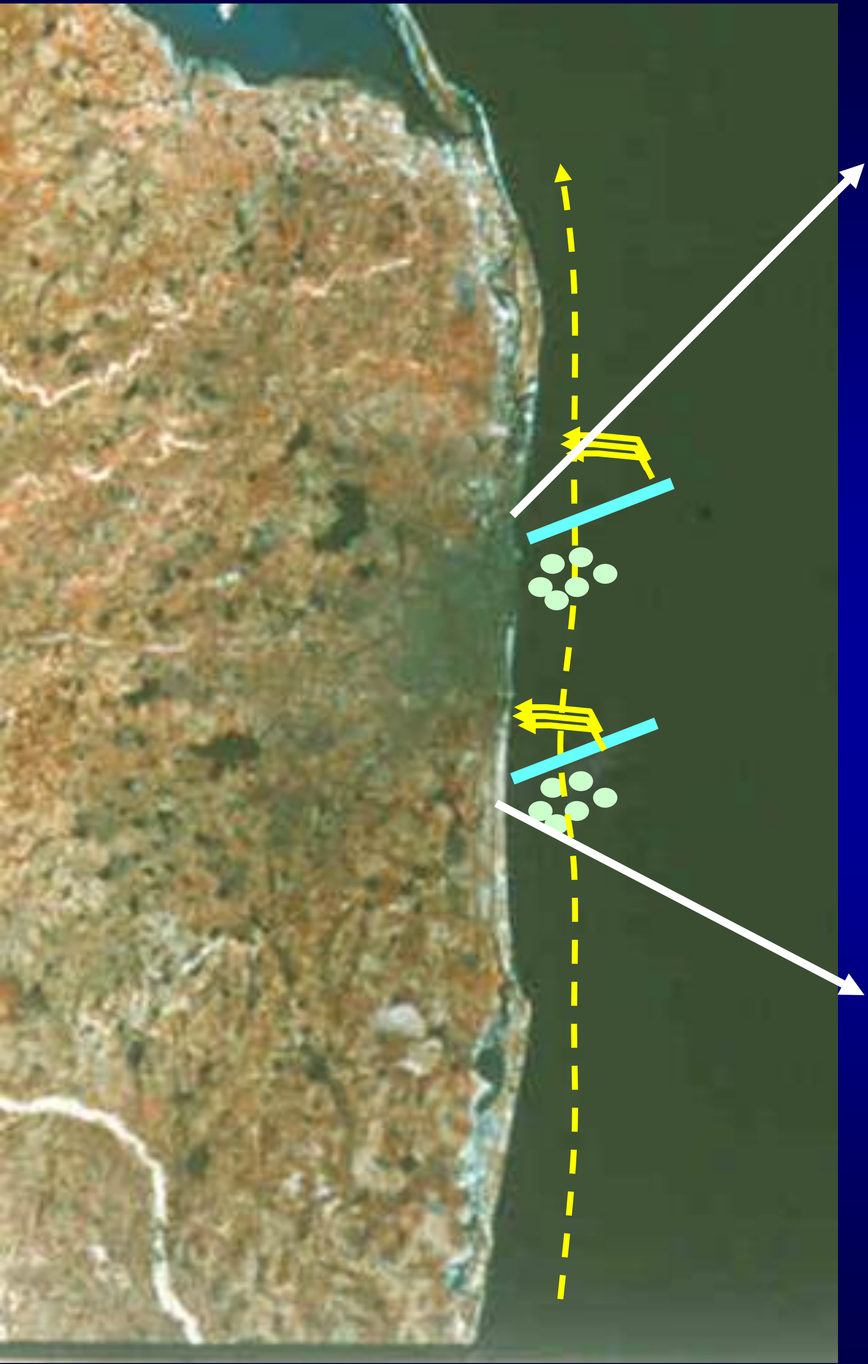
Due to construction of jetties since 1876

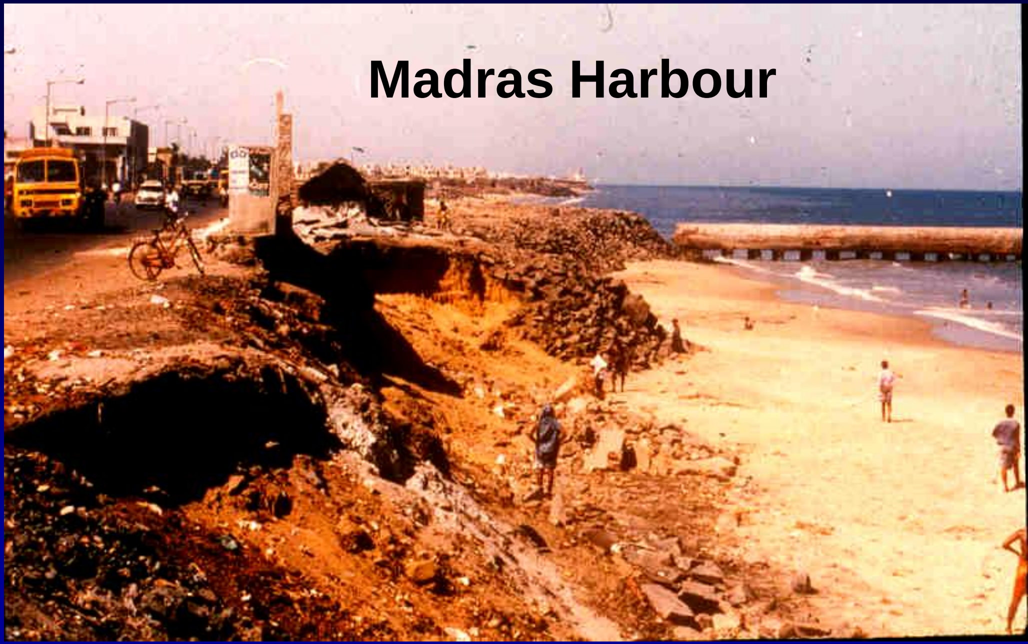
Accumulation of sand on the southern side results in shift of shore 10 mts/year

And severs erosion on the northern side of the harbor

MANGALORE HARBOR

Similar 500 m long jetty constructed in Mangalore cause accretion and erosion in the updrift and downdrift sides of the coast





Madras Harbour

Mahabalipuram

COASTAL PROTECTION

Usually carried out either to protect the existing beaches or to build up the Beaches lost due to erosion

- **Restoration of Beaches**
- **Protection of beaches**

RESTORATION OF BEACHES

Groynes:

Wooden, concrete and/or rock barriers or walls at right angles to the sea.

Groynes arrest littoral drift and make the shore line progress seaward till become parallel to the wave direction

(A) Groynes on the sand-starved coast of northern New Jersey have little obvious effect on shoreline stability.

SPACING OF GROYNES PLAYS A VITAL ROLE

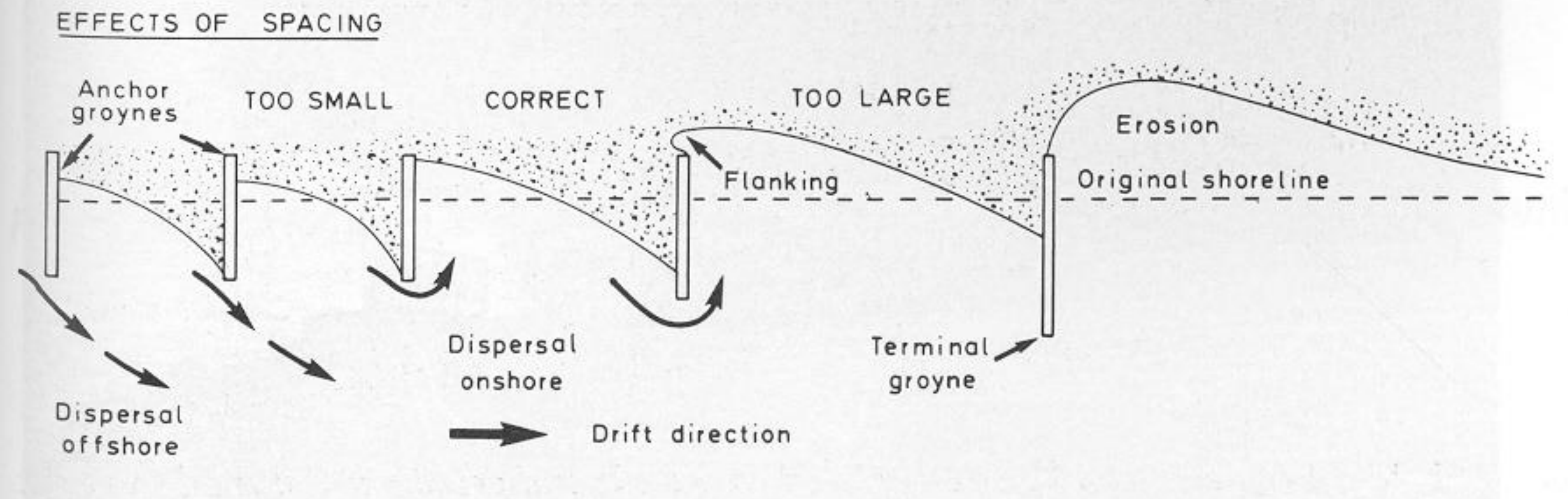


Figure 219. Of all groyne dimensions perhaps the effect of spacing is the most critical. Correct spacing is probably a function of wave parameters. Relatively small spacings encourage excessive seaward dispersal of sediment, relatively long spacings promote flanking. Terminal groynes are often responsible for downdrift erosion.

RIP RAP

Large rocks are piled or placed at the foot of cliffs, which are placed with native stones of the beach

GABIONS

Boulders and rocks are wired into mesh cages

When the seawater breaks on the gabion, the water drains through leaving sediment, losses its energy.

Gabions - wire mesh baskets filled with cobbles or crushed rock

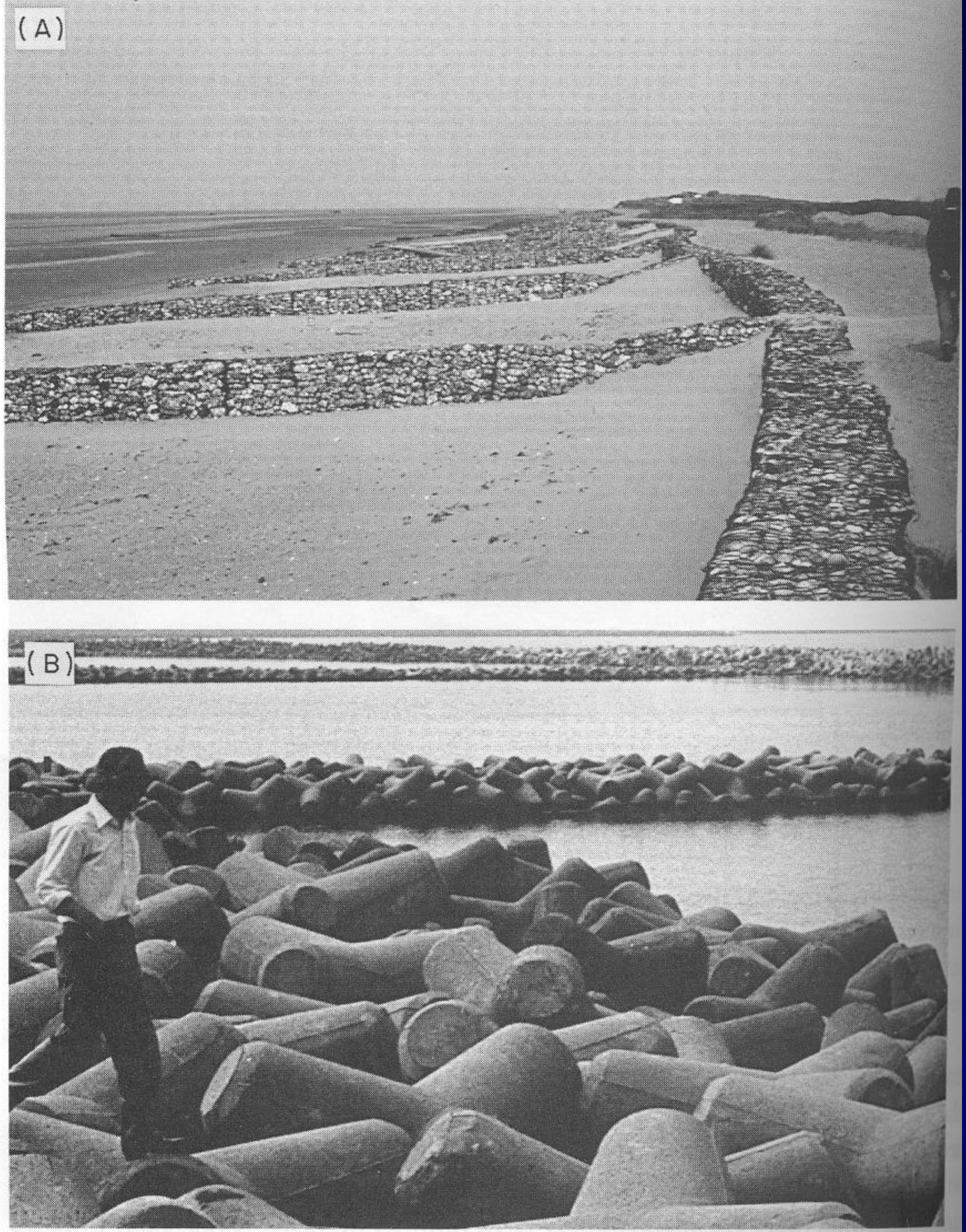


Figure 214. (A) Wire-frame gabions employed as a groyne system on a low-energy, macro-tidal coast in Norfolk, UK. (B) Tetrapods are used widely to protect the shore. Their large and irregular surface area helps wave dissipation, while the "legs" interlock to produce stability.

OFFSHORE BREAKWATER

Structures constructed parallel to the coastline in break water zone thereby reducing the magnitude of wave attack

Enormous concrete blocks and natural boulders are sunk offshore to alter wave direction and to filter the energy of waves and tides.

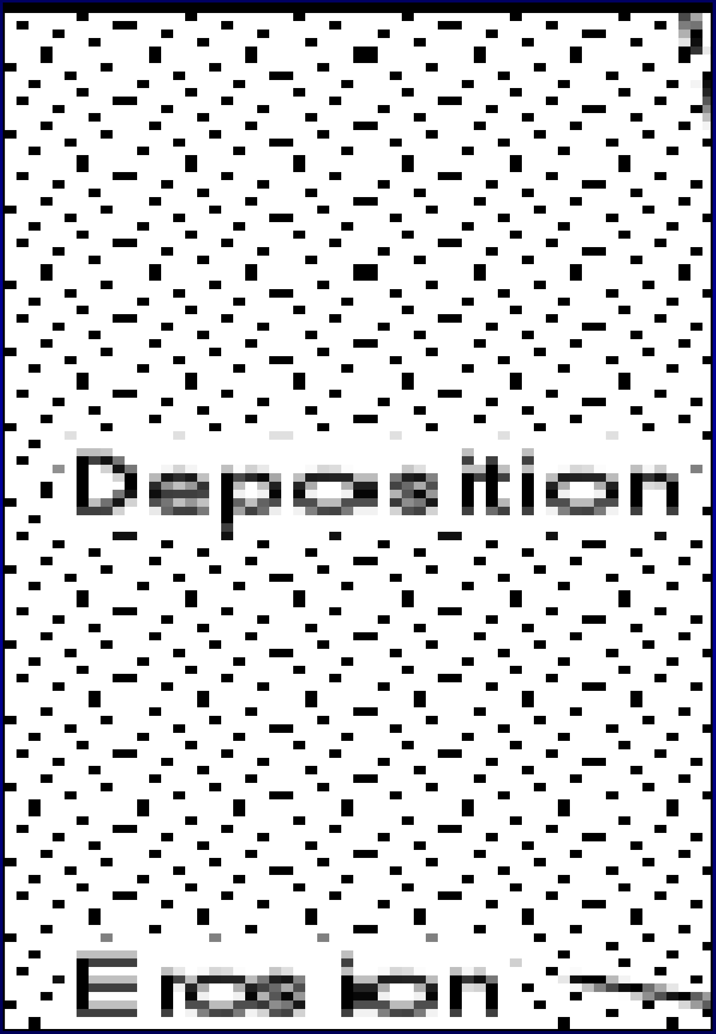
The waves brake further offshore and therefore reduce their erosive power.

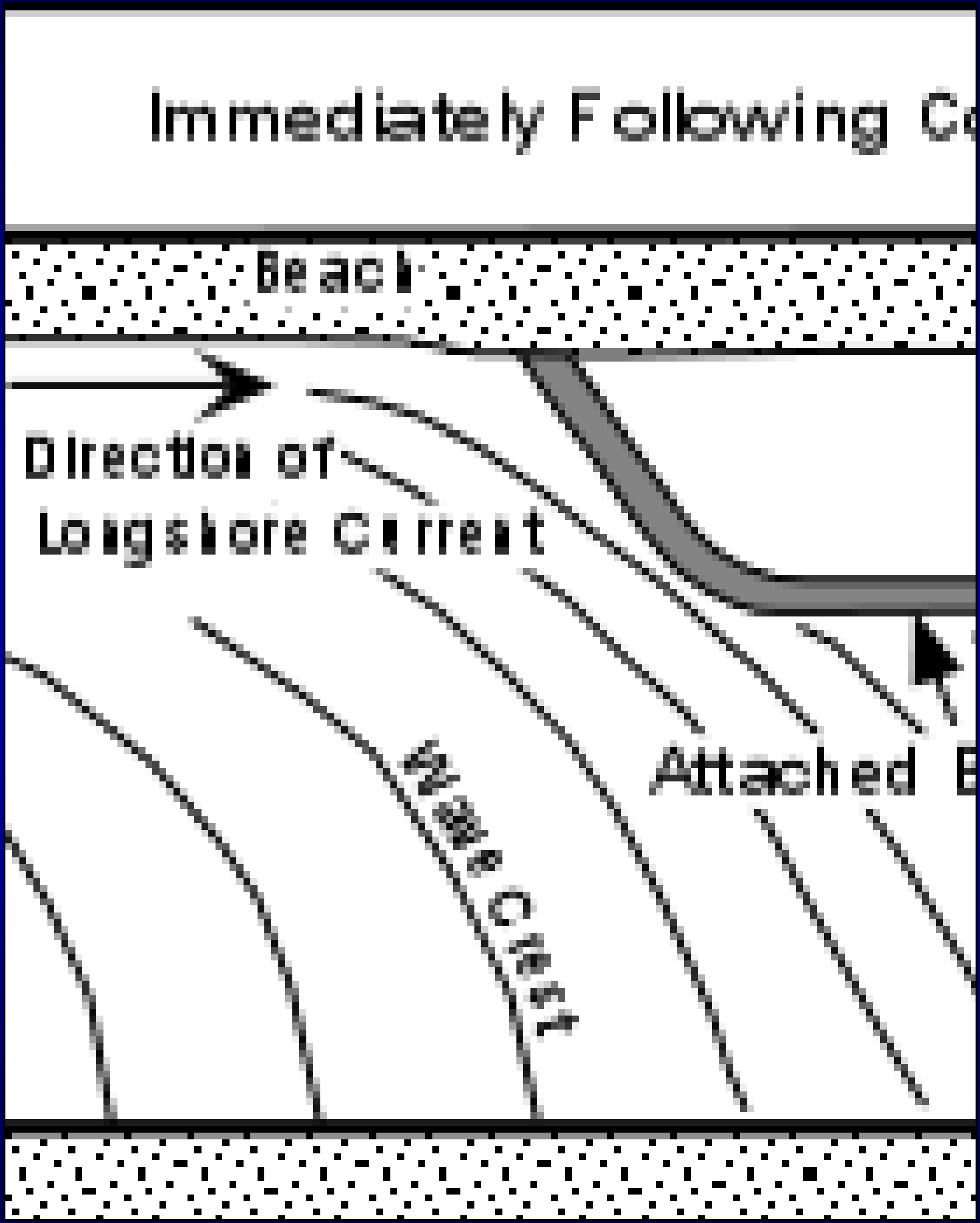
This leads to wider beaches

Nearshore breakwaters

Figure 213. The vertical granite seawall at St. Malo in northern France during an onshore gale. Note the line of wooden posts aimed at reducing the direct wave forces on the wall, and the partial clapotis in the nearshore zone.

LONGSHORE CURRENTS





Offshore Break waters

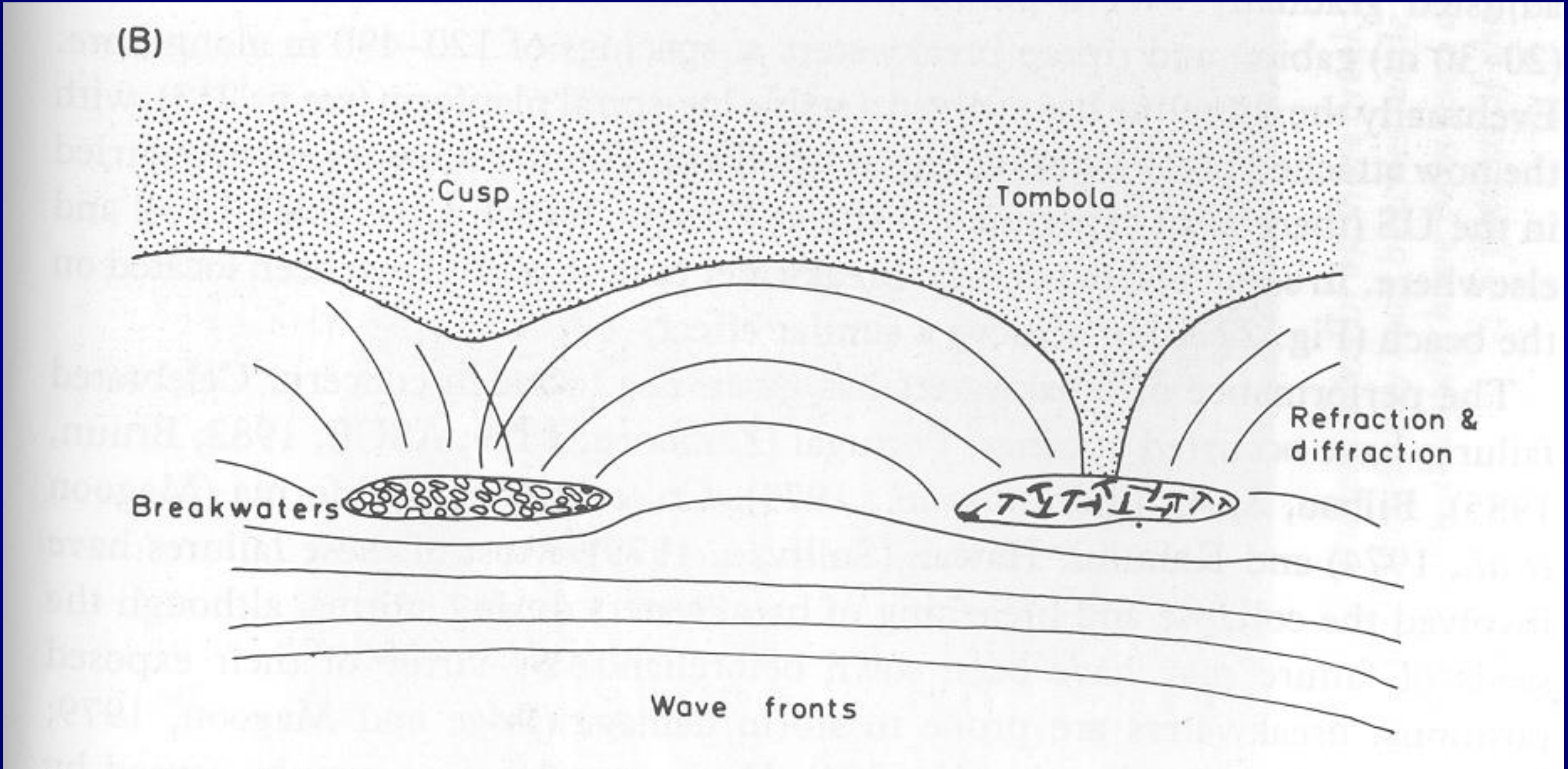


Figure 226. (A) Cross-section of an idealized rubble-mound breakwater to show the types of material that might be used in its construction. (B) Plan view of the effects of periodic offshore breakwaters, promoting wave caustics and sedimentation.

BEACH NOURISHMENT

This involves importing alien sand of the beach and piling it on top of the existing sand

The imported sand must be of a similar quality to the existing beach material so it can integrate with the natural processes occurring there, without causing any adverse effects

SAND DUNE STABILISATION

Vegetation encourages dune growth by trapping and stabilising blown sand.

Figure 230. South Lake Worth Inlet by-passing plant in 1977. Sand from the updrift (northern side) is pumped across the inlet and redeposited on the downdrift side.

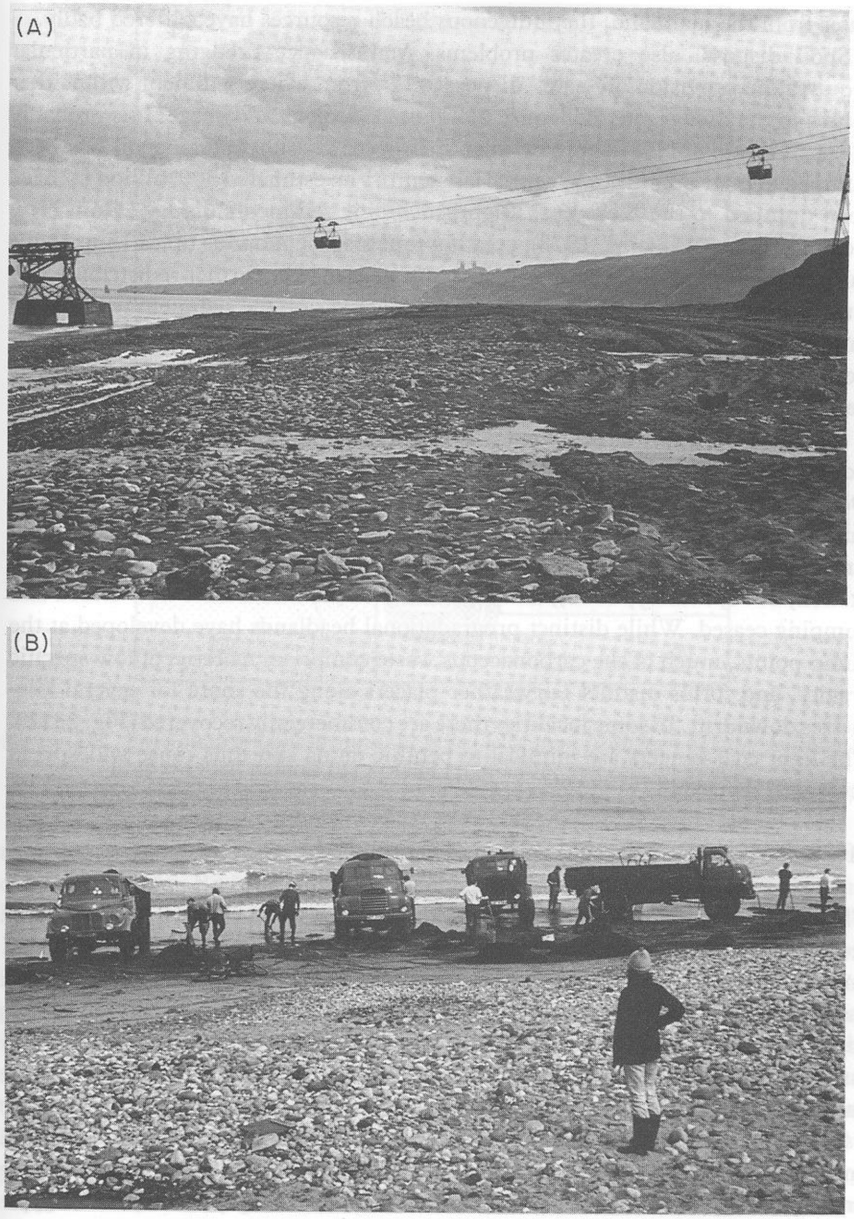


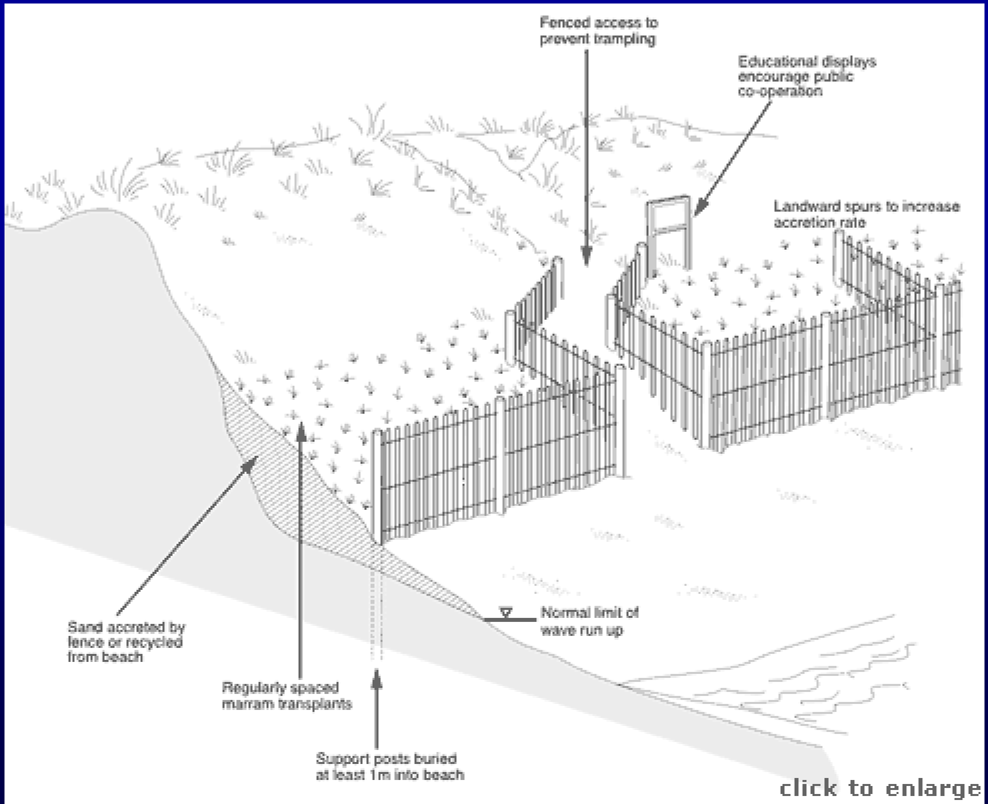
Figure 237. (A) The dumping of colliery waste onto the shore at Horden, Co. Durham has created a major depositional bulge on the coast. This colliery has now closed and dumping has ceased. (B) Sediment from Horden moves downcoast to Hartlepool, by which time it has been sorted, with the less dense coal fraction forming a commercially valuable surface placer across the beach.

Timber and geotextile

Stabilisation using grass plants.

Fencing

© Pamela Gore, 1998



PROTECTION TO BEACHES

SEA WALL

Walls,concrete /or stone, built at base of cliff or beach.

Often curved to resist and reflect the energy of the waves back out to sea

REVETMENTS

Consist of timber slants with a possible rock infill. Waves brake against the revetments, which dissipate, greatly absorbs the energy instead of reflecting.

Seawall / bulkhead / revetments

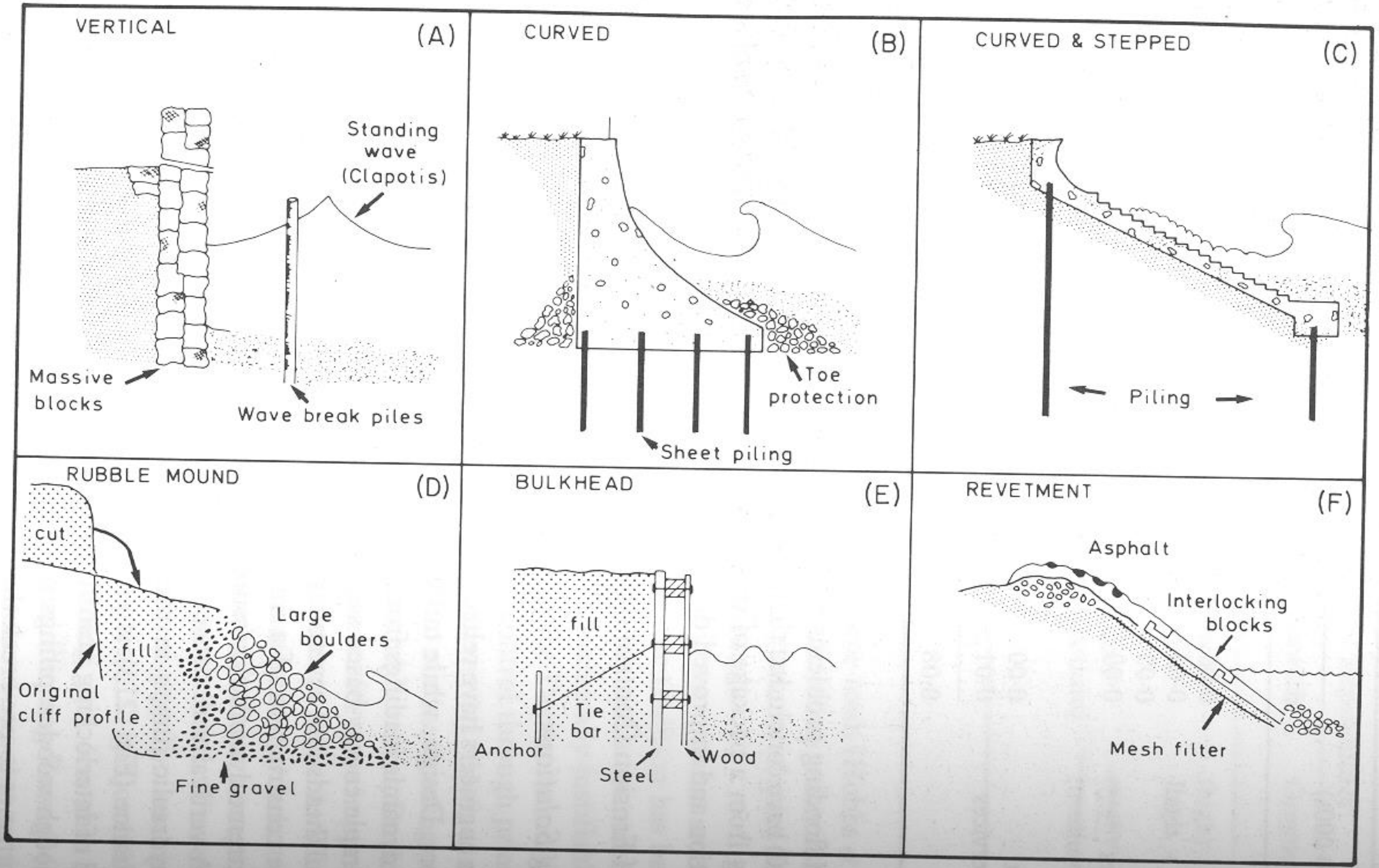
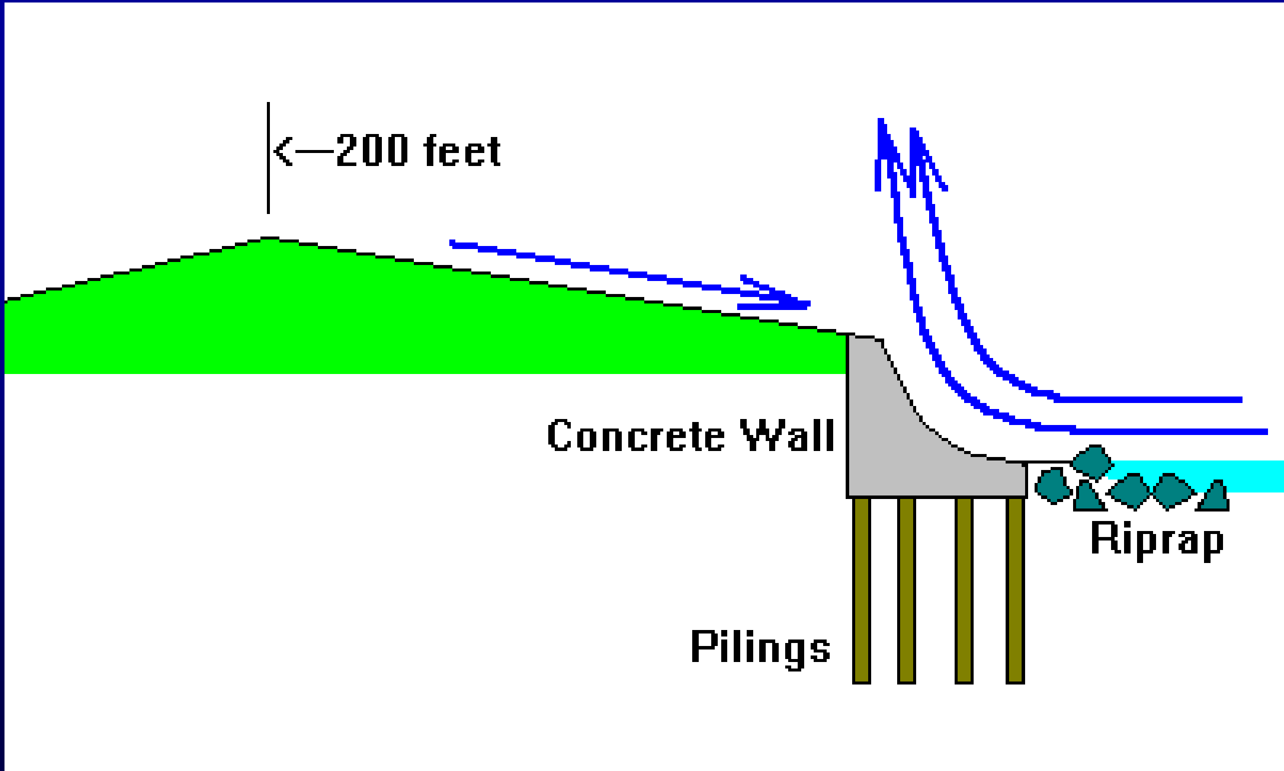


Figure 212. An energy based sequence of shore protection designs (high to low, A to F). (A) Vertical seawall constructed of resistant interlocking blocks. (B) Curved seawall with toe protection. (C) Curved and stepped wall secured by piling. (D) Rubble-mound or armouring plus regrading of the coastal slope. (E) Bulkhead of wood or steel. (F) Revetment made of armour blocks, gabions or asphalt.

Concrete and stone seawall.



ROCK REVENMENTS

Rock faced concrete revetment

Sand bags

COASTAL VULNERABILITY MAPPING

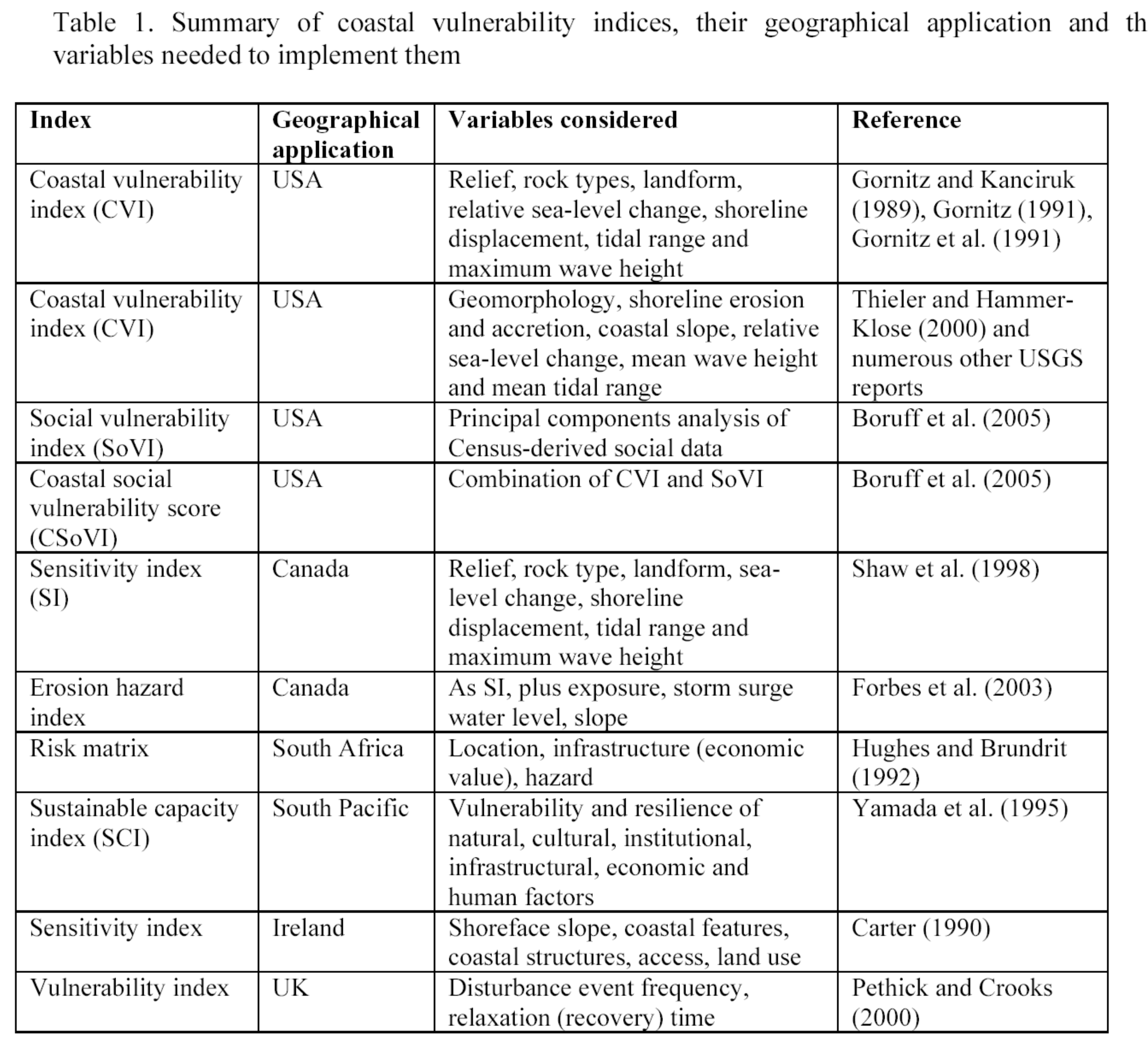
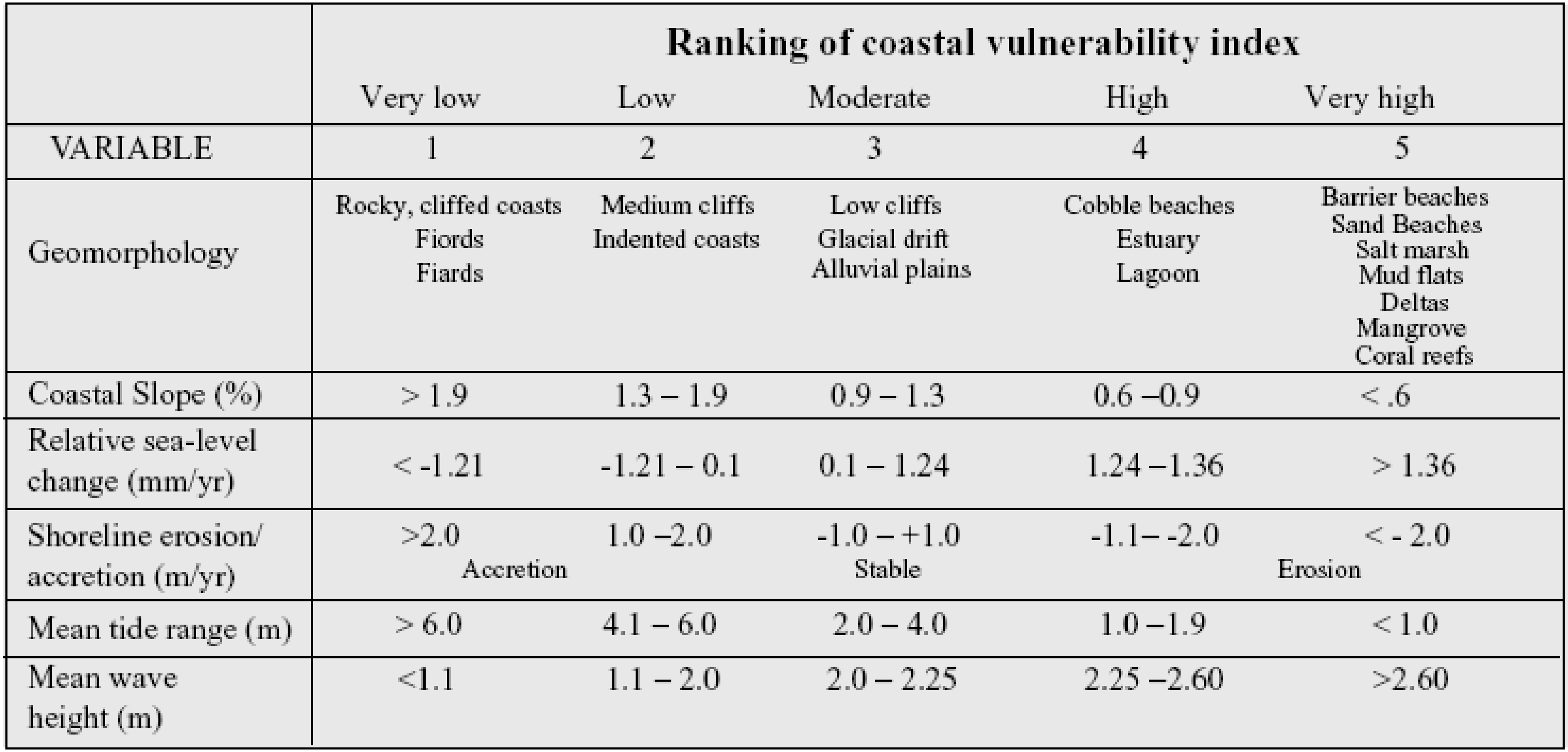


Table 1. Summary of coastal vulnerability indices, their geographical application and th variables needed to implement them

Index	Geographical application	Variables considered	Reference
Coastal vulnerability index (CVI)	USA	Relief, rock types, landform, relative sea-level change, shoreline displacement, tidal range and maximum wave height	Gornitz and Kanciruk (1989), Gornitz (1991), Gornitz et al. (1991)
Coastal vulnerability index (CVI)	USA	Geomorphology, shoreline erosion and accretion, coastal slope, relative sea-level change, mean wave height and mean tidal range	Thieler and Hammer-Klose (2000) and numerous other USGS reports
Social vulnerability index (SoVI)	USA	Principal components analysis of Census-derived social data	Boruff et al. (2005)
Coastal social vulnerability score (CSoVI)	USA	Combination of CVI and SoVI	Boruff et al. (2005)
Sensitivity index (SI)	Canada	Relief, rock type, landform, sea-level change, shoreline displacement, tidal range and maximum wave height	Shaw et al. (1998)
Erosion hazard index	Canada	As SI, plus exposure, storm surge water level, slope	Forbes et al. (2003)
Risk matrix	South Africa	Location, infrastructure (economic value), hazard	Hughes and Brundrit (1992)
Sustainable capacity index (SCI)	South Pacific	Vulnerability and resilience of natural, cultural, institutional, infrastructural, economic and human factors	Yamada et al. (1995)
Sensitivity index	Ireland	Shoreface slope, coastal features, coastal structures, access, land use	Carter (1990)
Vulnerability index	UK	Disturbance event frequency, relaxation (recovery) time	Pethick and Crooks (2000)

Ranking of coastal vulnerability index variables

(Thieler and Hammar-Klose, 2000)



	Ranking of coastal vulnerability index				
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand Beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Coastal Slope (%)	> 1.9	1.3 – 1.9	0.9 – 1.3	0.6 –0.9	< .6
Relative sea-level change (mm/yr)	< -1.21	-1.21 – 0.1	0.1 – 1.24	1.24 –1.36	> 1.36
Shoreline erosion/ accretion (m/yr)	>2.0 Accretion	1.0 –2.0	-1.0 – +1.0 Stable	-1.1– -2.0	< - 2.0 Erosion
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 –1.9	< 1.0
Mean wave height (m)	<1.1	1.1 – 2.0	2.0 – 2.25	2.25 –2.60	>2.60

$$CVI = \sqrt{((a*b*c*d*e*f)/6)}$$

Table 3. *Physical variables used to create the coastal physical vulnerability index (CVI).**

Variable	Measurement	Source
Mean tidal range	Meters	Tide gauges
Coastal slope	Percent	Topography, bathymetry
Rate of relative sea-level rise	Δ mean water elevation	Tide gauges
Shoreline erosion and accretion rates	Meters/year	Coastal Erosion Information System (CEIS)
Mean wave height	Meters	Wave Information Study (WIS)
Geomorphology (erodability)	Ordinal value	Geology, topography

* Based on data from Thieler and Hammer-Klose (1999, 2000a, 2000b).

Table 3. Ranking of coastal vulnerability index (CVI) variables for the Illawarra coast, NSW, Australia, adapted from the coastal risk classes of Gornitz (1991)

Category	**Very low**	**Low**	**Moderate**	**High**	**Very High**
VARIABLE	**1**	**2**	**3**	**4**	**5**
a1. Dune height (m)	≥ 30.1	20.1 - 30.0	10.1 - 20.0	5.1 - 10.0	0 – 5.0
a2. Barrier types	Transgressive	Prograded	Stationary	Receded	Mainland beach
a3. Beach types	Dissipative (D) Longshore bar trough (LBT)	Rhythmic bar beach (RBB)	Transverse bar rip (TBR)	Low tide terrace (LTT)	Reflective (R)
a4. Relative sea-level change (mm/yr)	≤ -1.1 Land rising	- 1.0 - 0.99	1.0 - 2.0 Eustatic rise	2.1 - 4.0	≥ 4.1 Land sinking
a5. Shoreline erosion/accretion (m/yr)	≥ + 2.1 accretion	1.0 - 2.0 Stable	-1.0 - + 1.0 Erosion	-1.1 - -2.0 erosion	≤-2.1 Erosion
a6. Mean tidal range (m)	≤ 0.99 Microtidal	1.0 - 1.9 Microtidal	2.0 - 4.0 Mesotidal	4.1 - 6.0 Mesotidal	≥ 6.1 Macrotidal
a7. Mean wave height (m)	0 - 2.9	3.0 - 4.9	5.0 - 5.9	6.0 - 6.9	≥ 7.0

RESULTS

Barrier types were classified based on knowledge of depositional environments and histories (Thom et al., 1978).

Five types of barriers were recognised; episodic transgressive, prograded, stationary, receded and mainland beach barriers.

Episodic transgressive dune barriers can be attributed to locally high rates of sand supply at the downdrift terminus of a littoral drift system, implying an abundant sand supply

Prograded barriers are typically characterised by multiple beach ridges (e.g. Moruya and Seven Mile Beaches).

Stationary barriers are generally narrower, characterised by dominantly vertical rather than lateral growth. They are recognised on the basis of the absence of significant morphological evidence of progradation

Receded barriers are thin marine sand deposits that overlie estuarine or back-barrier sediments which outcrop on the shoreface.

Mainland beach barriers are an end-member of the barrier types that comprise thin veneers of beach mantling a pre-Holocene erosional substrate (Roy et al., 1994).

Beach types **– A series of beach types (also called states as a beach may vary from one type to another over time) have been described by Short (1993, 1999). The 6 types are: Dissipative (D), Longshore Bar and Trough (LBT), Rhythmic Bar and Beach (RBB), Transverse Bar and Rip (TBR), Low Tide Terrace (LTT) and Reflective (R) beaches.**

Dissipative beaches have wide surf zones with shore parallel bars and channels with an abundant median to fine sand. An example is the northern part of Seven Mile beach. They tend to be relatively stable systems with low frequency of shoreline displacement events and spatially continuous, parallel, back-beach foredune scarps.

Intermediate beaches occupy states between the fully dissipative and reflective. They are characterized by rip circulation, crescentic-transverse bars and megacusps. Examples are Stanwell Park, Coledale, Bulli, Perkins, Warilla, mid Seven Mile and Moruya Beaches.

Reflective beaches are characterized by barless surfzone and steep, narrow, cusped or bermed beach. Fishermans Beach is an example, although not included in this study.

SALTWATER INTRUSION

Salt water intrusion

Mass transport of saline waters into zones previously occupied by fresher water is defined as salt water intrusion (stewart 1999).

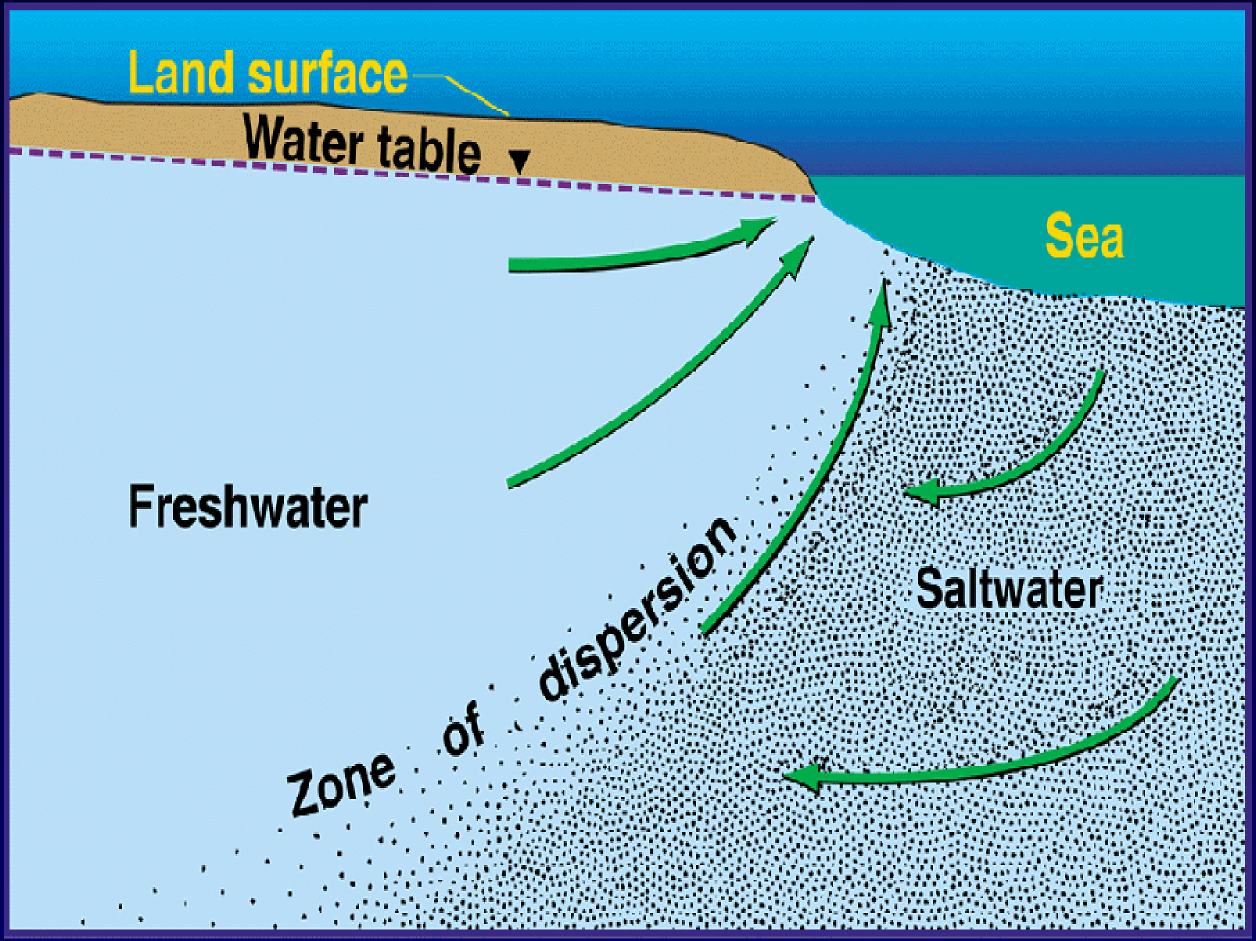
Sea water mixing with fresh water in coastal aquifer

Intrusion of sea water into the coastal aquifer system – may be considered as a type of environmental pollution due to human activities or/and to physical factors.

Salt Water Intrusion….

- The problem of saltwater intrusion was recognized as early as the 19th century,
- Because saltwater has high concentrations of total dissolved solids and certain inorganic constituents, it is unfit for human consumption and many other anthropogenic uses.
- The encroachment of saline water into freshwater aquifers most often is caused by over-pumping from coastal wells.
- Saltwater intrusion is a particularly acute problem in an island setting.

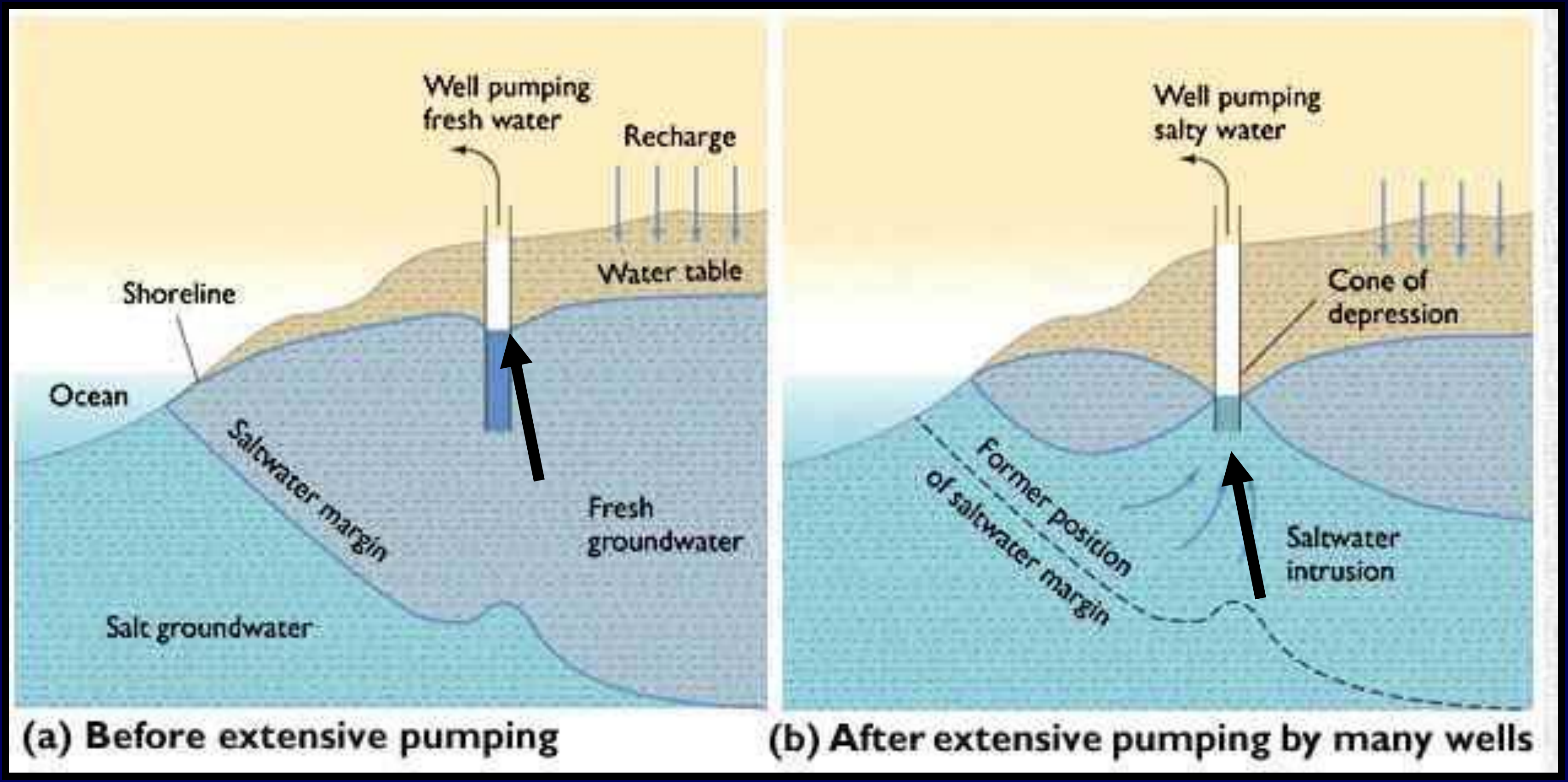
Conceptual Model of Saltwater Intrusion (*Cooper*, 1964)



Saltwater circulates from the sea to the transition zone.

Induced by mixing processes at the transition zone, saltwater then flows back to the sea.

Salt Water Intrusion



Pumping causes a cone of depression and draws the salt water upwards into the well

Reasons for salt water intrusion

- Rapid decline in rain fall along coastal zone
- High groundwater extraction / over use of gw along coastal aquifers
- Low natural recharge rate along coastal aquifers
- Drainage of irrigation water along coastal aquifer zones
- Construction of coastal roads and their drainage systems
- Unorganized drainage conditions in riverine, delta or estuarine areas
- Alluvial landscapes and natural sedimentation which determine the nutrient and energy flows in coastal areas are increasingly reduced
- Degradation of coastal wet lands through aquaculture forms, forest degradation, settlement construction, etc.

- Tidal wave action
- Fractures and faults extending from land to ocean could act both as leaky aquifer and path ways for salt water intrusion
- Permeable rock types or stratigraphy and their thickness along coast
- Existing folded structures along coast
- Sea level rise due to increase in temperature and subsequent melting of ice in the polar regions

Presence of salinity in coastal aquifers can be detected by

(a) **Geophysical methods**
- Resistivity method

(b) **Geochemical investigations**
- Chemical composition of groundwater
- Isotope studies (age of water to identify the source of salinity)

Mapping of salt water intruded areas

Conducting geophysical resistivity survey – gridwise along coast

Use of remote sensing in preparation of geomorphology, landuse/cover, soil, drainage and slope maps

Collection of field data such as groundwater level, hydrogeochemistty, etc.

Use of GIS in thematic data integration

GEOPHYSICAL MAPPING OF SALTWATER INTRUSION IN EVERGLADES NATIONAL PARK

David V. Fitterman
Maria Deszcz-Pan

U.S. Geological Survey
Box 25046 MS 964
Denver, CO 80225

Phone: 303-236-1382
FAX: 303-236-1409
e-mail: fitter@musette.cr.usgs.gov

Keywords: saltwater intrusion, airborne geophysics, borehole geophysics, electromagnetics, time-domain electromagnetic, induction logs, specific conductance, water quality, monitoring wells

1. ABSTRACT

The mapping of saltwater intrusion in coastal aquifers has traditionally relied upon observation wells and collection of water samples. This approach may miss important hydrologic features related to saltwater intrusion in areas where access is difficult and wells are widely spaced, such as the Everglades. To map saltwater intrusion in Everglades National Park, a different approach has been used. We have relied heavily on helicopter electromagnetic (HEM) measurements to map lateral variations of electrical resistivity, which are directly related to water quality. The HEM data are inverted to provide a three-dimensional resistivity model of the subsurface. Borehole geophysical and water quality measurements made in a selected set of observations wells are used to determine the relation between formation resistivity and specific conductance of pore water. Applying this relation to the 3-D HEM resistivity model produces an estimated water-quality model. This model provides constraints for variable density, ground-water models of the area. Time-domain electromagnetic (TEM) soundings have also be used to map saltwater intrusion. Because of the high density of HEM sampling (a measurement point every 10 meters along flight lines) models with a cell size of 100 meters on a side are possible, revealing features which could not be recognized from either the TEM or the observation wells alone. The very detailed resistivity maps show the extent of saltwater intrusion and the effect of former and present canals and roadbeds. The HEM survey provides a means of quickly obtaining a synoptic picture of saltwater intrusion, which also serves as a baseline for monitoring the effects of Everglades restoration activities.

Saltwater intrusion mapping and modeling using

1. **Helicopter Based EM measurements**
2. **Electromagnetic Sounding**
3. **Groundwater samples**

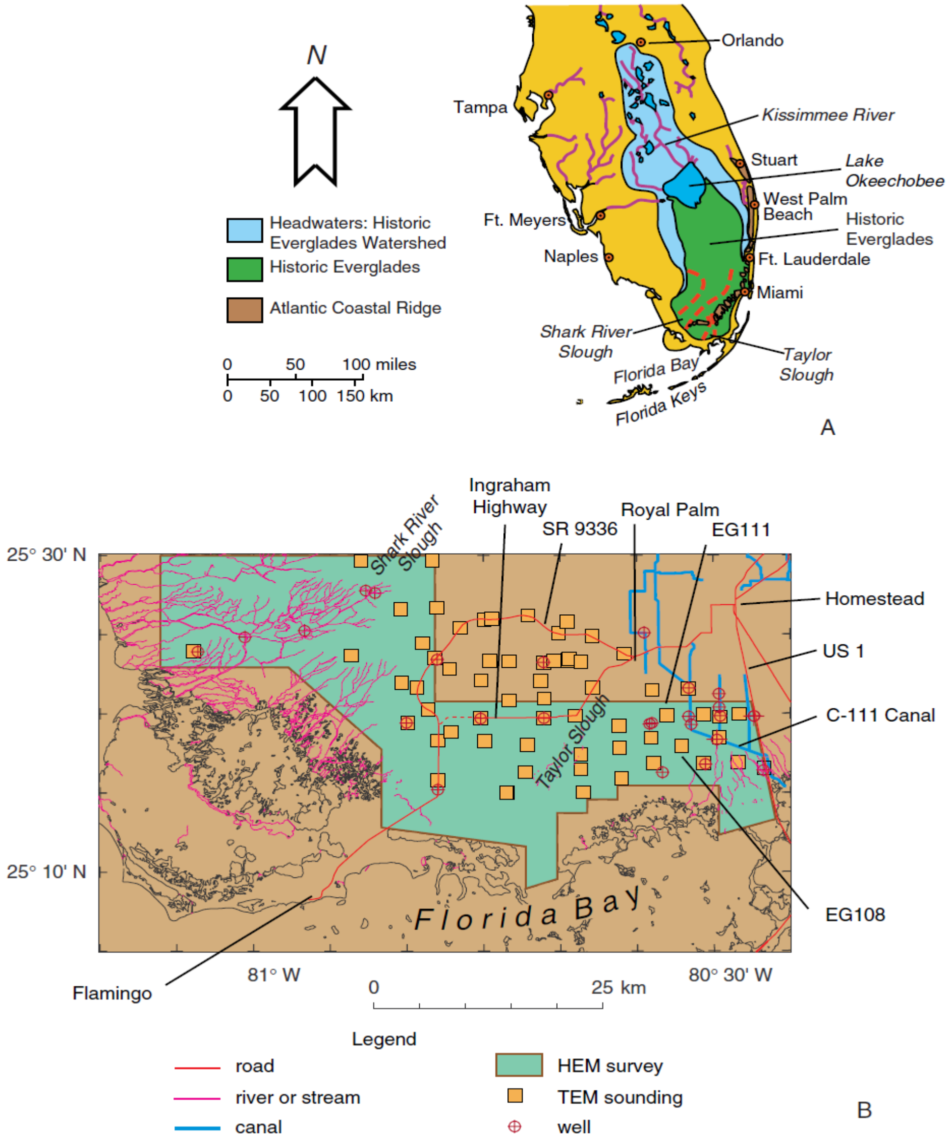


Figure 1 a) Map of south Florida and the historic Everglades.
b) Location map showing the December 1994 HEM survey, TEM soundings, and observations wells in and near Everglades National Park used in this study. Note the location of TEM soundings EG108 and EG111.

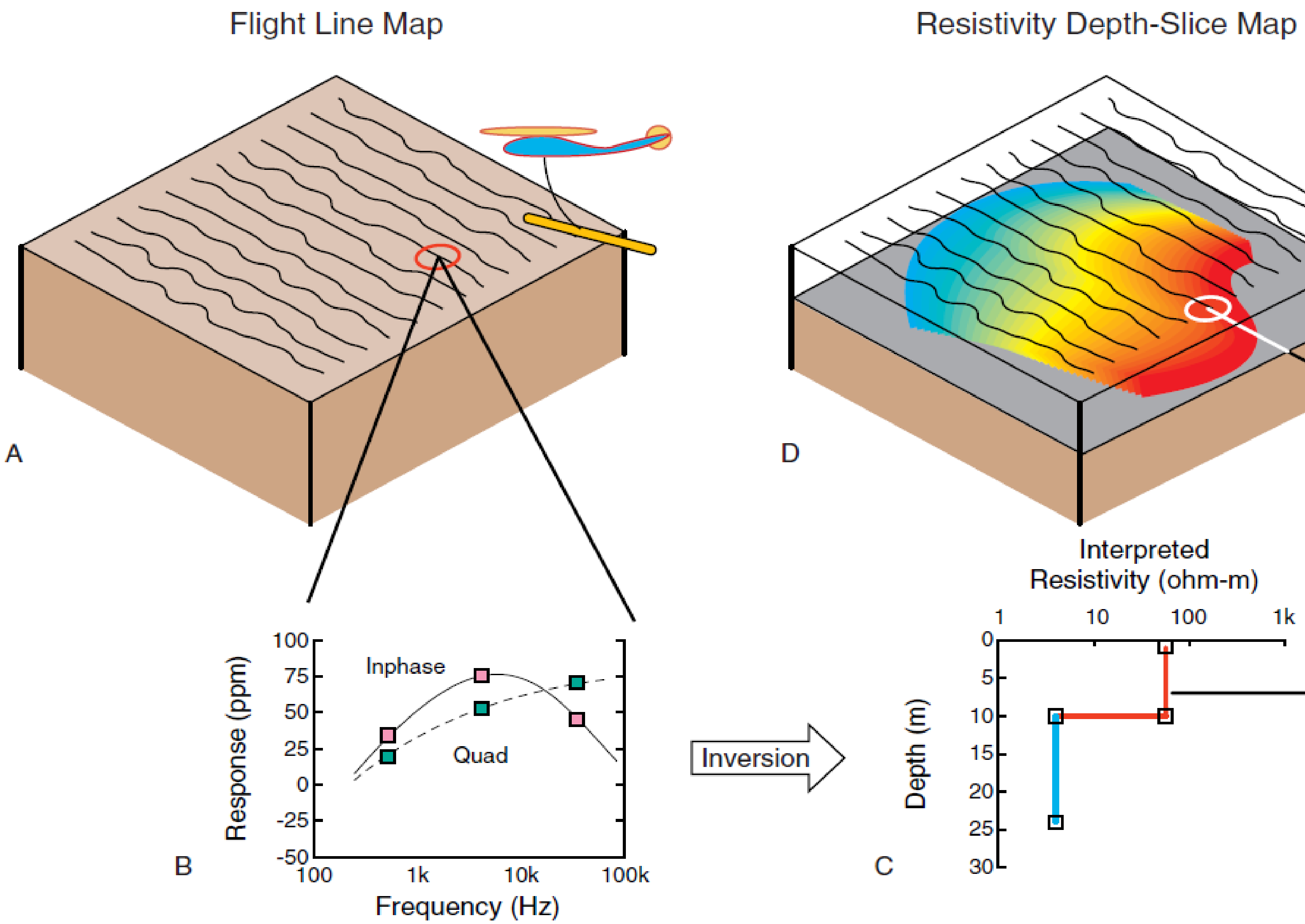


Figure 2 Schematic representation of HEM data collection and interpretation. a) Flight lines are flown along parallel lines spaced 400 m apart. b) The bird measures the inphase and quadrature electromagnetic response at several frequencies. c) The measured response is used to determine the resistivity-depth function by a process called inversion. d) The resistivity-depth functions are combined to produce an interpreted resistivity depth-slice map.

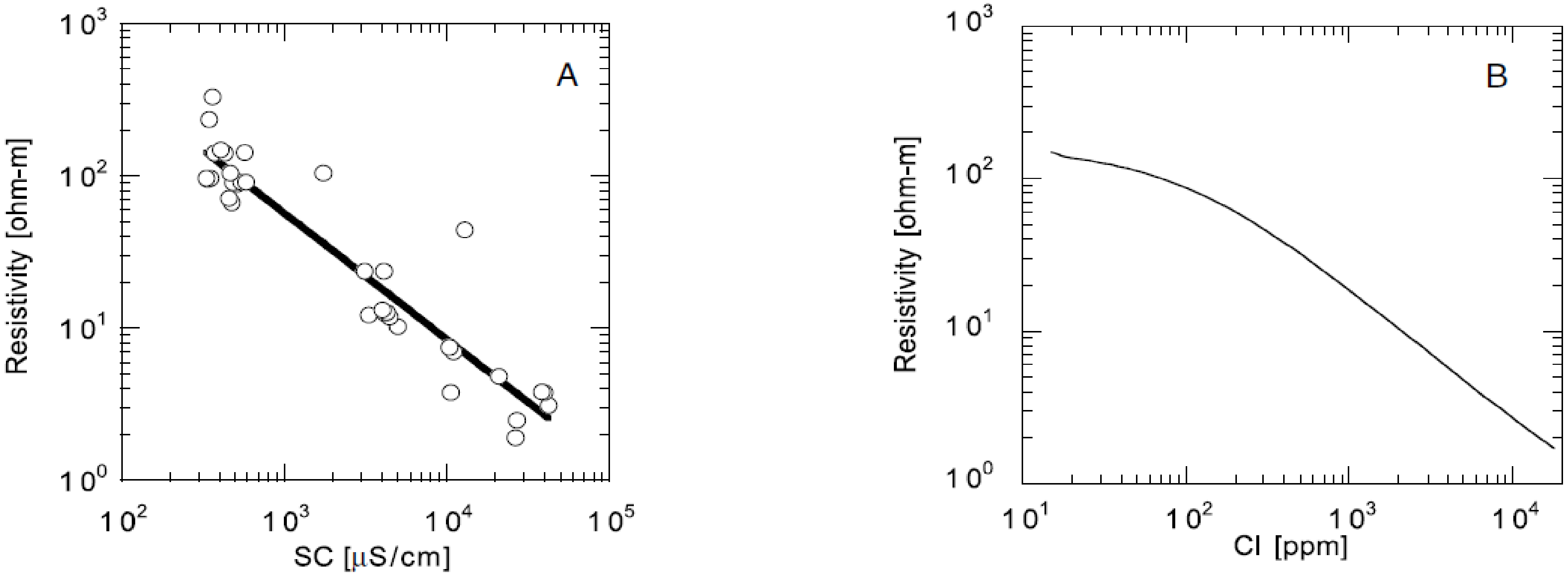


Figure 3 a) Formation-resistivity-pore-water conductivity relation from induction logs and water samples. The solid line is the power-law relation which best fit the data.
b) Derived formation resistivity-chloride relationship for the surficial aquifer in the study area.

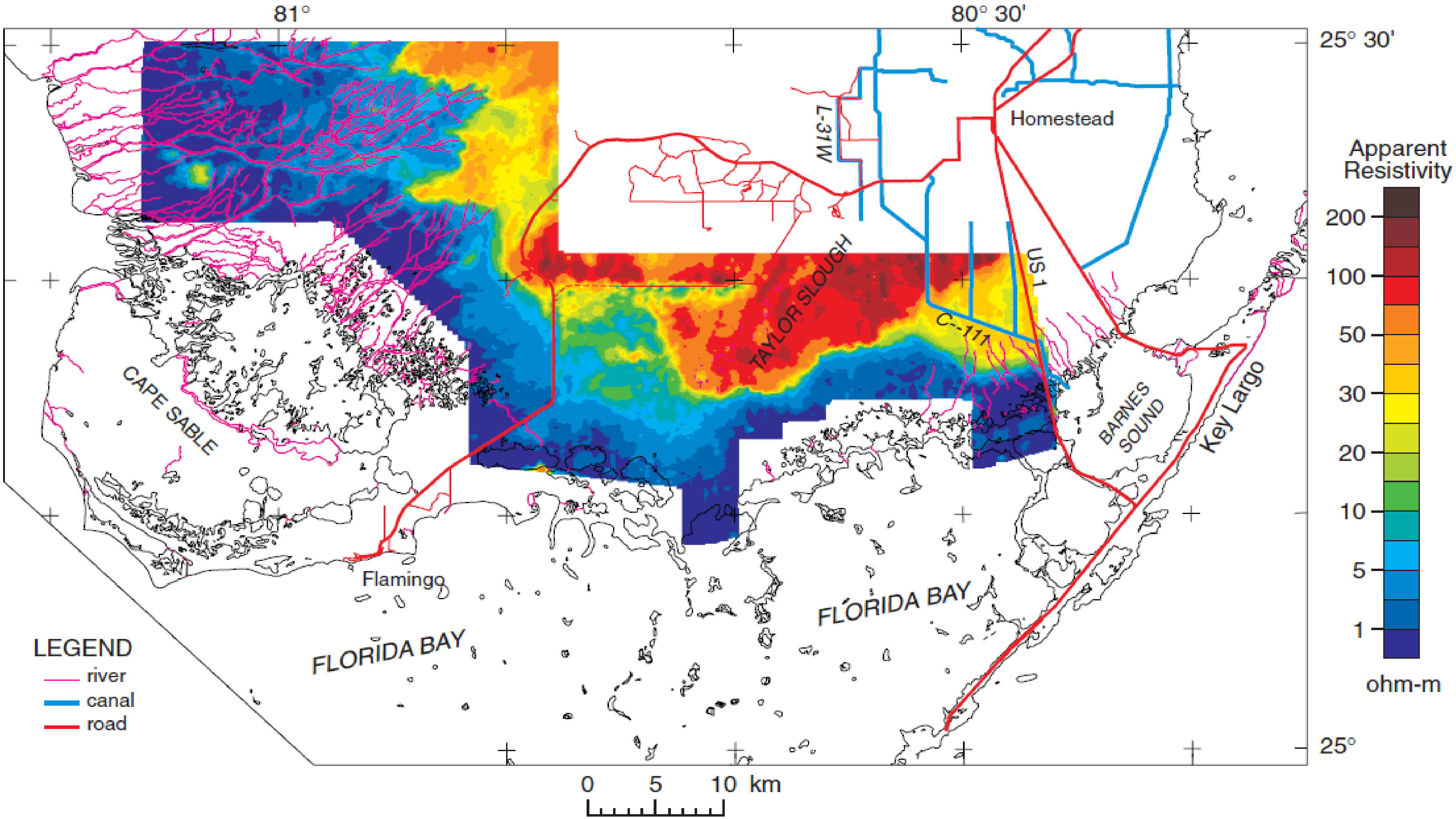


Figure 4 HEM 56-kHz apparent resistivity map from Everglades National Park.

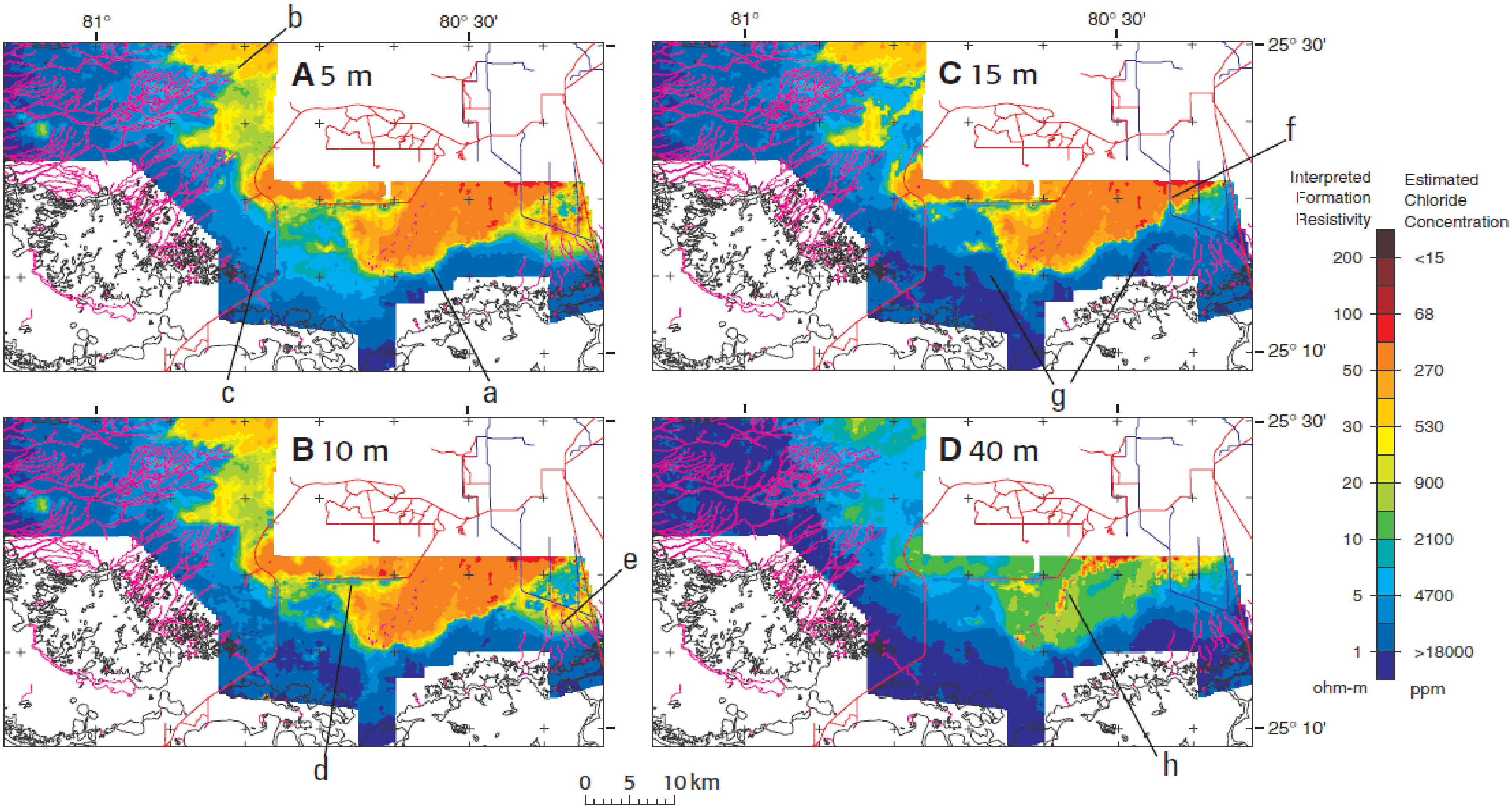


Figure 5 Interpreted HEM resistivity-depth-slice map from Everglades National Park for depths of 5 m (A), 10 m (B), 15 m (C), and 40 m (D). Annotated features are discussed in the text.

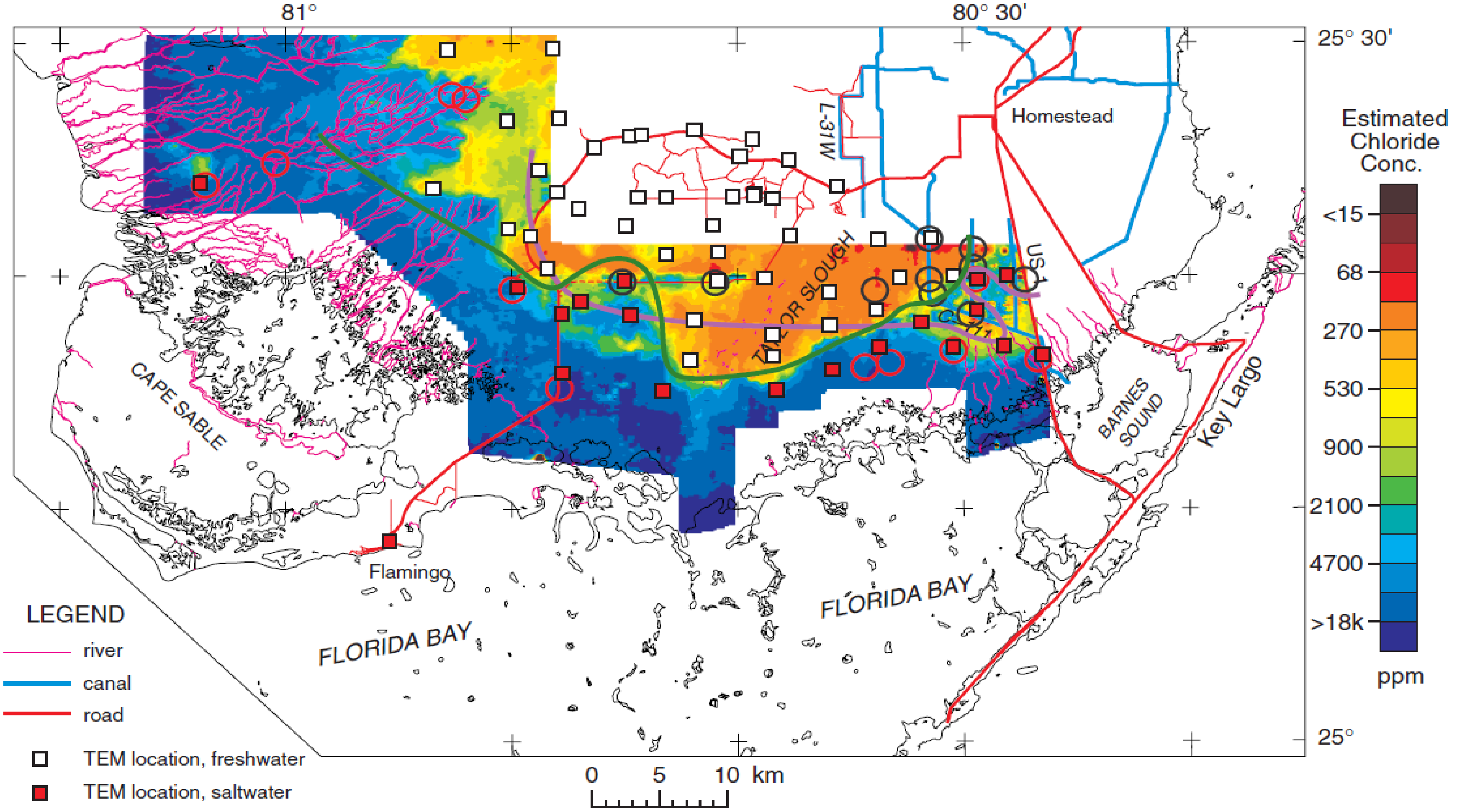


Figure 7 Location of the FWSWI in Everglades National Park based on well, TEM, and HEM data. The HEM data is from the 10-m depth slice. The color bar shows the estimated chloride concentration.

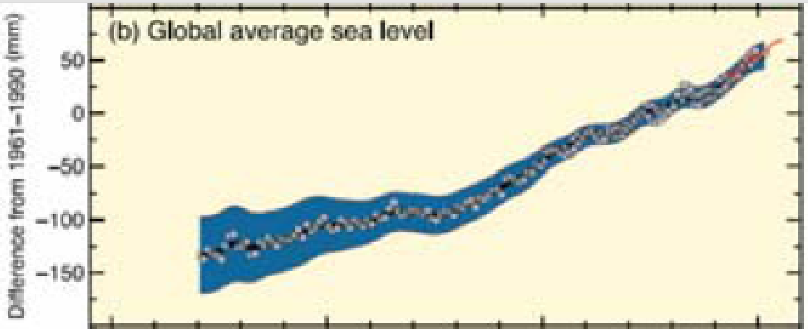
8. CONCLUSIONS

Ground and airborne electromagnetic methods have been shown to be an effective method for mapping saltwater intrusion in Everglades National Park. The results of these surveys and well measurements are in agreement. The HEM data with its high sampling density presents a detailed picture of saltwater intrusion that, in turn, allows identification of factors influencing the location of the FWSWI. The interpreted resistivity maps, when combined with well log data to determine the formation-resistivity-chloride-concentration relationship, provide a means of developing a three-dimensional water quality model that can be used in ground-water modeling studies.

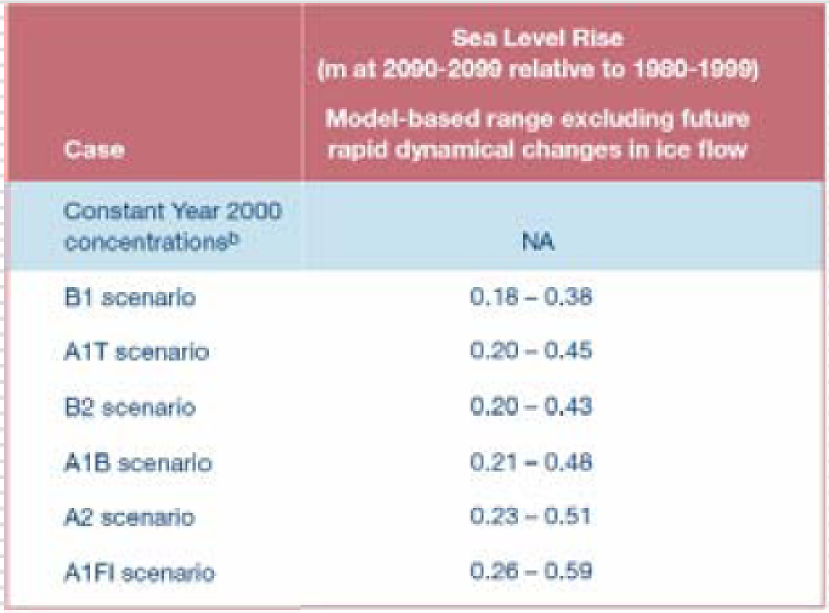
Because the HEM data were collected in less than five days, the results essentially provide a snapshot of the entire aquifer. At present, there is no other way to obtain an equivalent synoptic picture. Equally significant, this survey can be used as a baseline against which future surveys can be compared. Such comparisons are a means of assessing the effects of ecosystem restoration activity on saltwater intrusion beneath the Everglades.

Global Climate Change, Sea Level Rise and Saltwater Intrusion (*IPCC*, 2007)

- Projected sea-level rise due to climate change is several mm/yr over the next century.
- This has serious consequences for people living in coastal areas through the effects of flooding, coastal erosion and saltwater intrusion.



Ghyben-Herzberg principle (based on hydrostatic equilibrium): sea-level rise of 2.5 mm → thinning of the fresh water wedge by ~10 cm.

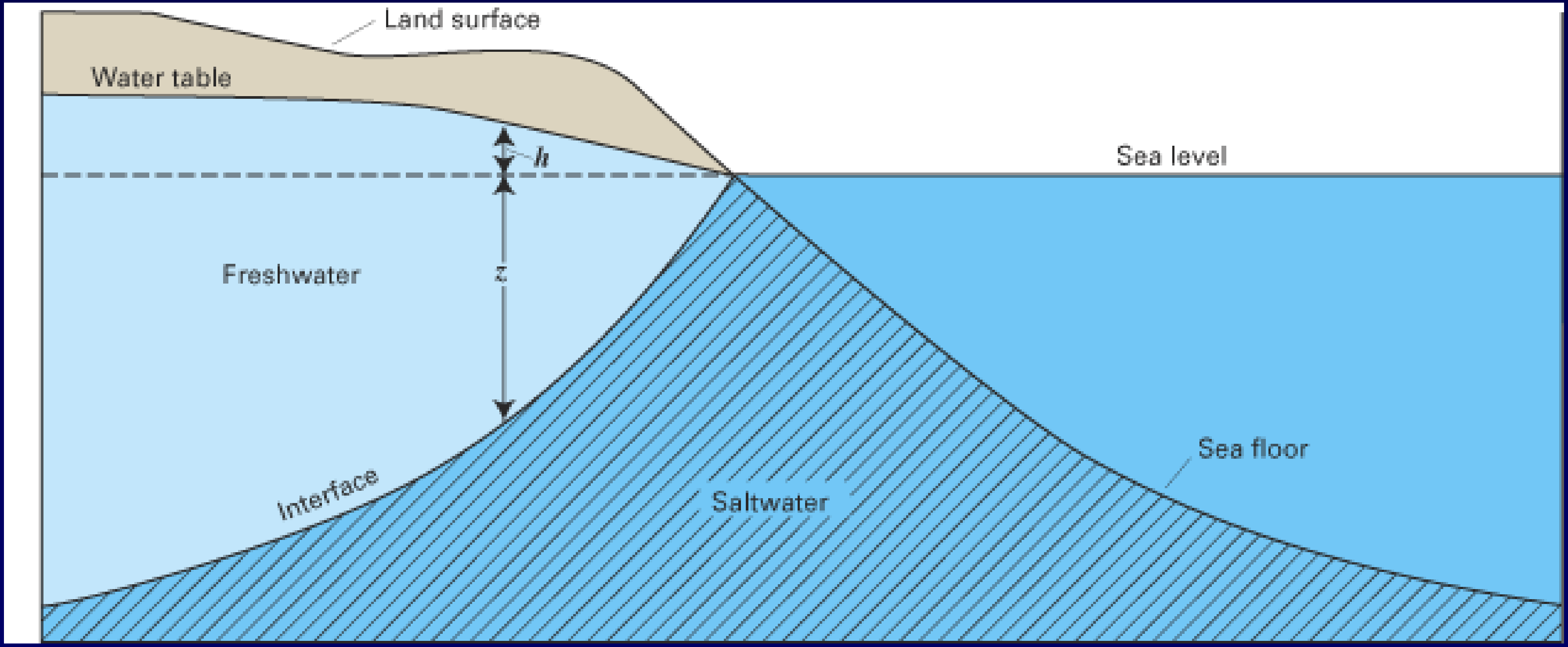


Case	Sea Level Rise (m at 2090-2099 relative to 1980-1999) Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations[b]	NA
B1 scenario	0.18 – 0.38
A1T scenario	0.20 – 0.45
B2 scenario	0.20 – 0.43
A1B scenario	0.21 – 0.48
A2 scenario	0.23 – 0.51
A1FI scenario	0.26 – 0.59

Ghyben-Herzberg relation

The first physical formulations of saltwater intrusion were made by W. Badon-Ghijben (1888, 1889) and A. Herzberg (1901), thus called the Ghyben-Herzberg relation.

They derived analytical solutions to approximate the intrusion behavior, which are based on a number of assumptions that do not hold in all field cases.

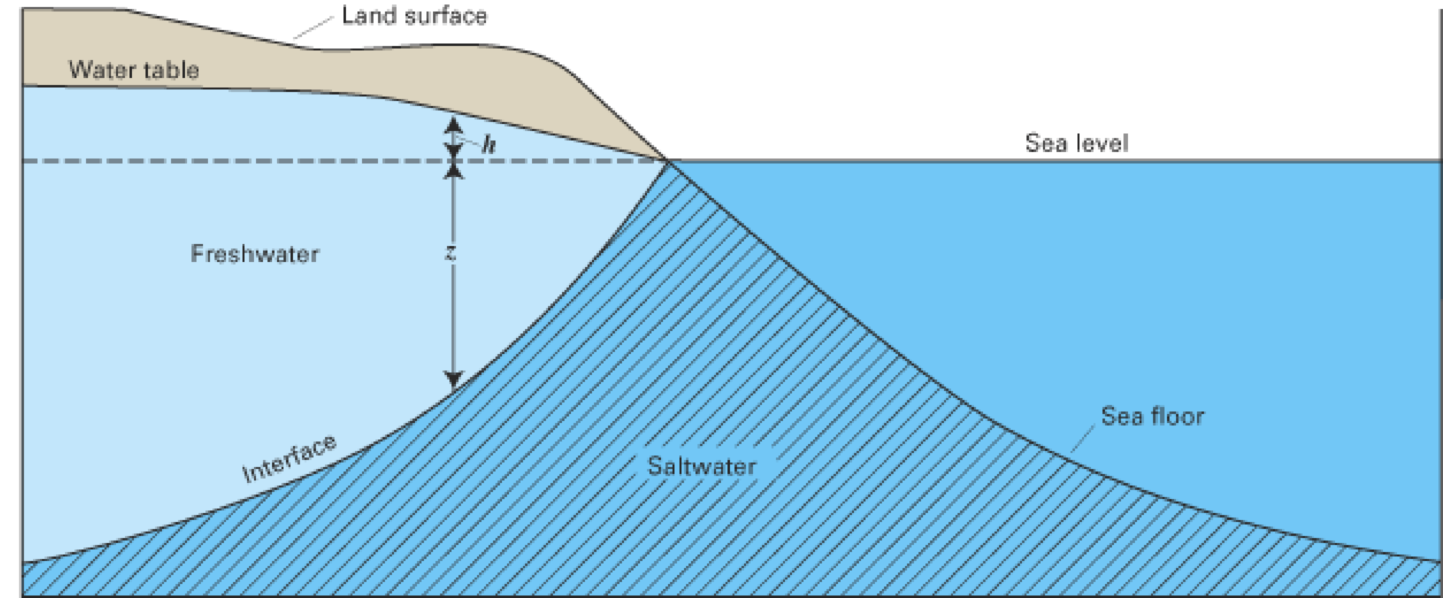


Ghyben-Herzberg relation

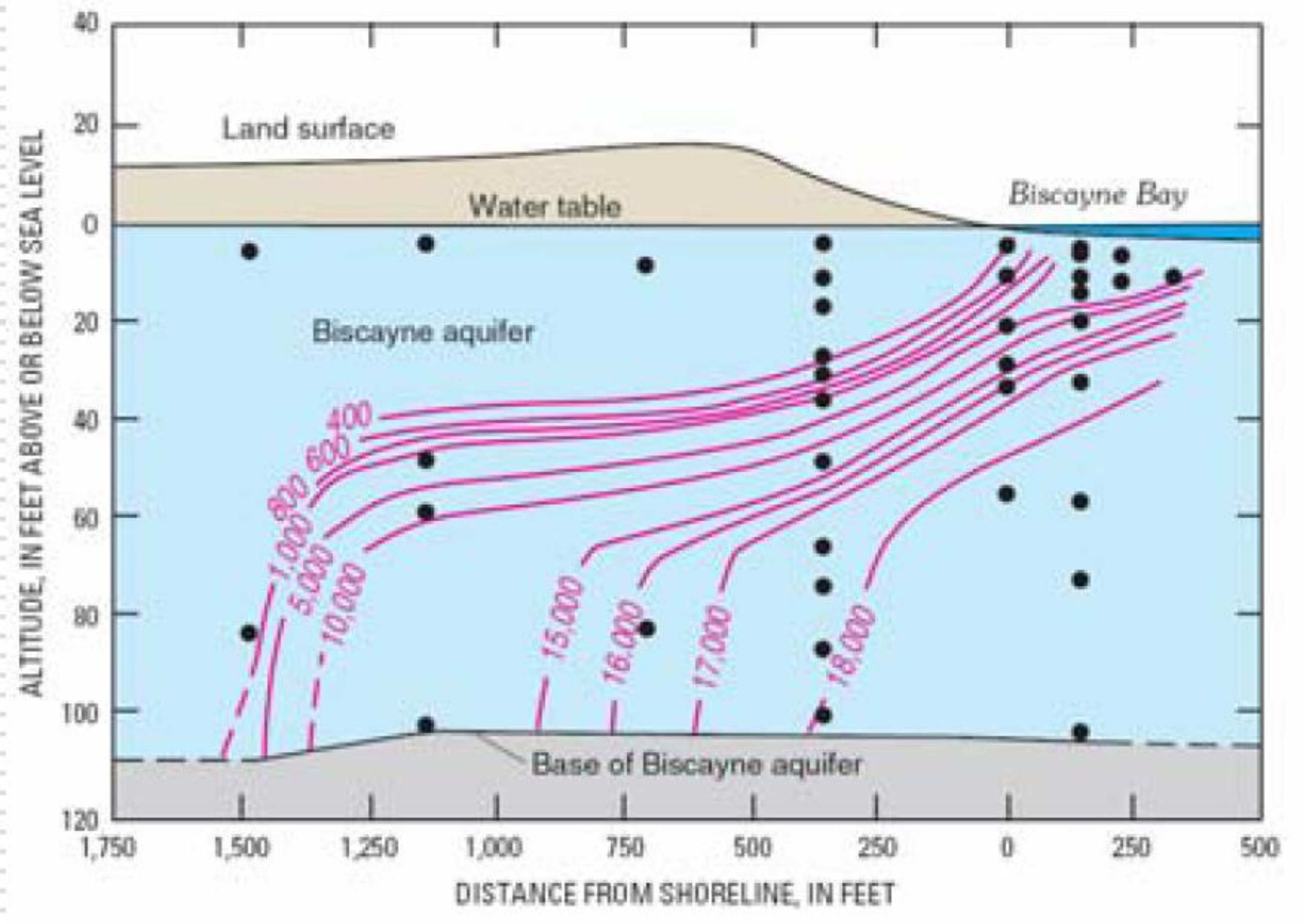
The thickness of the freshwater zone above sea level is represented as *h* and that below sea level is represented as *z*. The two thicknesses *h* and *z*, are related by ρ*f* and ρs where ρ*f* is the density of freshwater and ρs is the density of saltwater. Freshwater has a density of about 1.000 grams per cubic centimeter (g/cm3) at 20 °C, whereas that of seawater is about 1.025 g/cm3. The equation can be simplified to

Z = (Pf/(ps-pf)) * h, Z = 40h, if h = 1 then Z = 40, h = 2 then Z = 80

The Ghyben-Herzberg ratio states, for every foot of fresh water in an unconfined aquifer above sea level, there will be forty feet of fresh water in the aquifer below sea level.

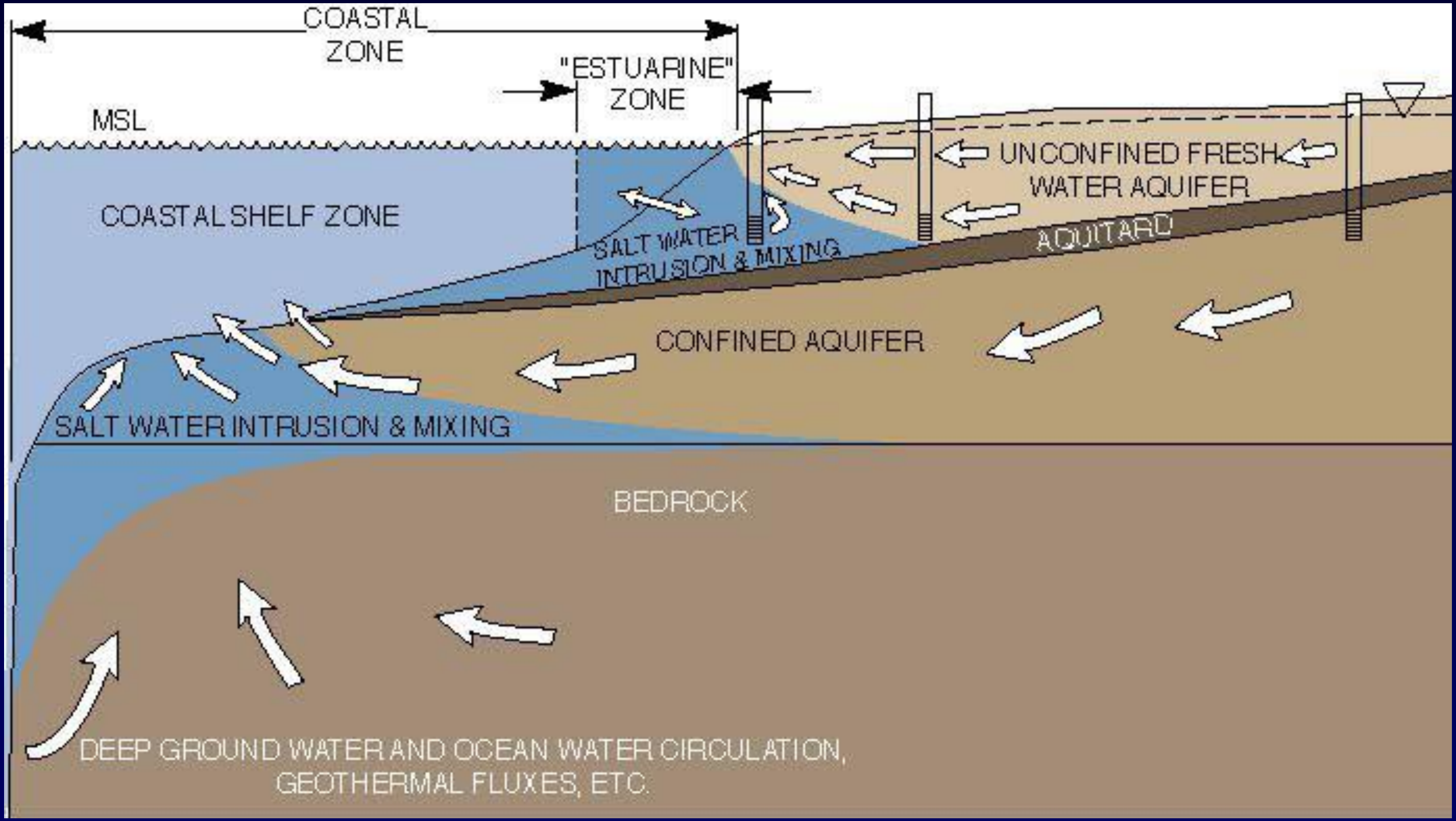


Geochemical Signature of the Spatial Distribution of Saltwater Encroachment



Spatial distribution of chloride concentration (ppm) from measurements on water samples extracted from numerous wells

Dynamic Interplay of Saltwater Intrusion and Submarine Groundwater Discharge



- SGD is driven by hydraulic gradient in the coastal aquifer
- Oceanic forces can induce tidal pumping and waves
- Mixing of the two can significantly impact the fluid chemistry of the ecosystem

Quantity and Quality of Groundwater in Coastal Ecosystems

The encroachment of saline water into a coastal aquifer is modulated by submarine groundwater discharge.

Coastal ecosystems undergo degradation from anthropogenic causes, including population growth and urbanization, pollution (untreated human waste, toxic waste), eutrophication (enhanced nutrient loading from agriculatural run-off, sewage and burning of fossil fuels).

Unlike surface discharge, there is a scarcity of data on the magnitude of SGD and its role as a source of dissolved solids, nutrients and contaminants.

VULNERABILITY EVALUATION by GALDIT METHOD

Groundwater occurrence (aquifer type; unconfined, confined or leaky confined)

Aquifer hydraulic conductivity

Depth to water level above the sea

Distance from the shore (distance inland perpendicular from shoreline)

Impact of existing status of sea water intrusion in the area and

Thickness of the aquifer.

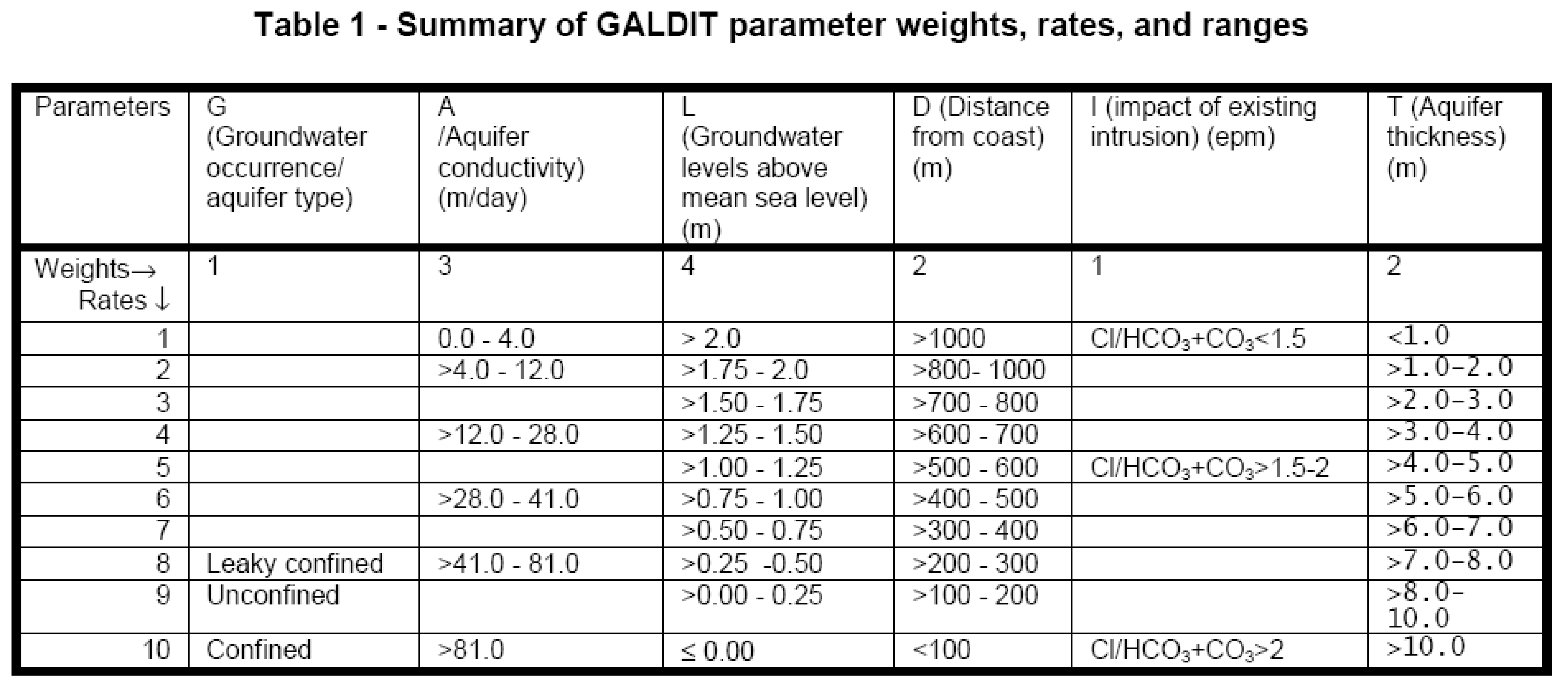


Table 1 - Summary of GALDIT parameter weights, rates, and ranges

Parameters	G (Groundwater occurrence/ aquifer type)	A /Aquifer conductivity) (m/day)	L (Groundwater levels above mean sea level) (m)	D (Distance from coast) (m)	I (impact of existing intrusion) (epm)	T (Aquifer thickness) (m)
Weights→ Rates ↓	1	3	4	2	1	2
1		0.0 - 4.0	> 2.0	>1000	$Cl/HCO_3+CO_3<1.5$	<1.0
2		>4.0 - 12.0	>1.75 - 2.0	>800- 1000		>1.0-2.0
3			>1.50 - 1.75	>700 - 800		>2.0-3.0
4		>12.0 - 28.0	>1.25 - 1.50	>600 - 700		>3.0-4.0
5			>1.00 - 1.25	>500 - 600	$Cl/HCO_3+CO_3>1.5\text{-}2$	>4.0-5.0
6		>28.0 - 41.0	>0.75 - 1.00	>400 - 500		>5.0-6.0
7			>0.50 - 0.75	>300 - 400		>6.0-7.0
8	Leaky confined	>41.0 - 81.0	>0.25 -0.50	>200 - 300		>7.0-8.0
9	Unconfined		>0.00 - 0.25	>100 - 200		>8.0-10.0
10	Confined	>81.0	≤ 0.00	<100	$Cl/HCO_3+CO_3>2$	>10.0

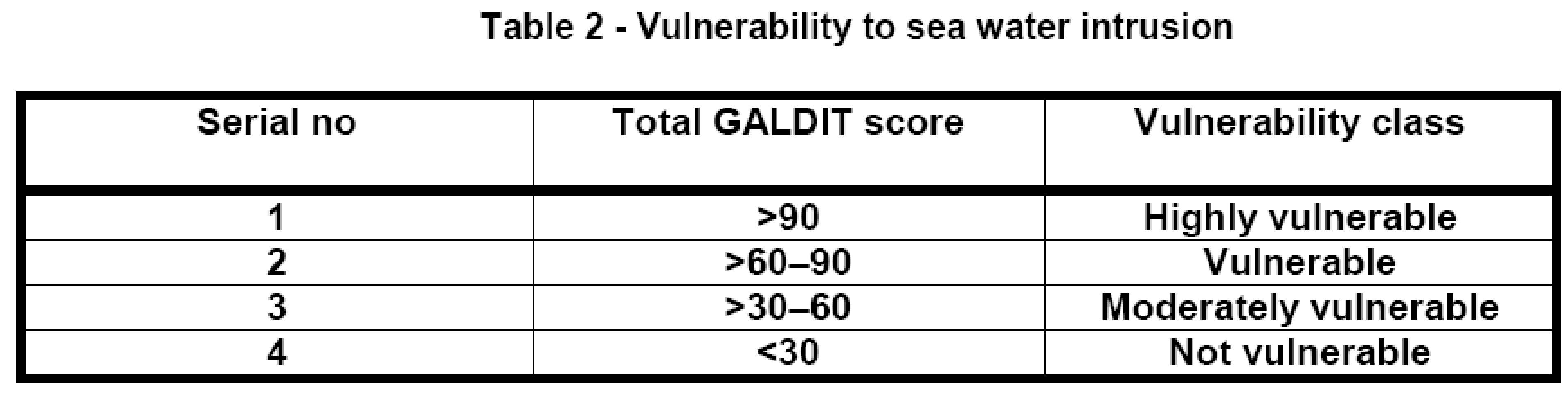


Table 2 - Vulnerability to sea water intrusion

Serial no	Total GALDIT score	Vulnerability class
1	>90	Highly vulnerable
2	>60–90	Vulnerable
3	>30–60	Moderately vulnerable
4	<30	Not vulnerable

Most popular models for seawater intrusion

- SUTRA
- SEAWAT
- HST3D
- FEFLOW

Recently released **Visual MODFLOW Pro 4.1** now integrates SEAWAT-2000 to solve variable density flow problems, such as seawater intrusion modeling projects.

MEASURES

1. Potable water development – conservation of coastal wet lands

2. Ground water recharge

Water spreading (spreading surplus water into large tanks and ponds)

Injection method by injecting water into aquifer system (Adequate care on the water quality has to be taken)

Construction of percolation ponds and check dams to allow percolation.

Areas of artificial recharge should be based on the intensity of the problems, the course of action should follow.

Identifying the coastal aquifers and demarking the area for development and vulnerable areas needing immediate remedies

Collection of hydrogeological, hydrological, land use, water use and ecological data

Applying management technique and monitoring