

Impact of 2004 coseismic coastal uplift on the mangrove cover along the North Andaman Islands

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Abstract

The December 2004 earthquake and the subsequent tsunami have incurred devastating impacts on vital habitats along the Indian coastal region, where few of them are irreversible. The earthquake has uplifted the northern Andaman coast, resulting in a drastic reduction of tidal water influx into the adjoining mangrove-laden mudflats. Satellite images of the period from 2003 to 2019 were used to assess the impact of coastal upliftment on the northern Andaman mangroves. Through satellite data analysis, we report a loss of 6500 ha of northern Andaman mangroves. Tidal hydrodynamics simulation under the post-earthquake scenario showed a vast area of mudflats deprived of tidal influx. This reduction in the tidal inundation has incurred a gradual and permanent mangrove area degradation. The earthquake impact on the mangroves was not spontaneous, but a gradual process, where the mangroves were intact until March 2006. The earthquake and the resultant coastal uplift have significantly altered the coastal geomorphology as well as the plant demography of the study area. Field visit revealed the terrestrial vegetation growth along the erstwhile mudflats, and vast areas of mangrove peat are observed, surrounded by successions of marshy and terrestrial plants. As mangroves are preferred habitat for diverse marine and terrestrial organisms and act as a vital food source and juvenile shelters for various fish species, the extensive loss of mangrove area may adversely affect a large scale biological ecosystem.

Introduction

Mangroves, as described by UNEP (2014), are the type of tropical forest, which are uniquely positioned at the dynamic interface of land and sea. These salt-tolerant plants help to regulate coastal flooding and erosion, thus protecting the inland coastal communities from natural hazards. Mangroves are self-generating and self-perpetuating littoral formation, which plays a major role in the global cycle of carbon, nitrogen, and sulphur (Coastal Zone of India, 2012). They also act as a habitat supporting the life of a diverse group of flora and fauna. In addition, mangroves are recognised for their economic functions by contributing to the livelihood of coastal folks in terms of forest produce and fish resources. The study by Anneboina and Kumar (2017) estimated the marginal effect of mangroves on total marine fish output in India as 1.86 tonnes per hectare per year from which the percentage contribution of mangroves to marine fish output was calculated as 23 percent in India in 2011.

The mangrove habitat is facing fatal threats globally and is reported to disappear at an annual rate of 0.66% (Kathiresan, 2018). Romanach et al. (2018) explored the status of global mangrove cover and the efforts to protect them, while Kathiresan (2018) discusses on the present status of Indian mangrove forest and success stories of its conservation and management strategies. Van Lavieren et al. (2012) have detailed on the different threats faced globally by the mangrove habitat. A large section of coastal management plans consider mangrove forest as low-value space and are converted into urban, aquaculture and agricultural land. Natural calamities like cyclone and tsunami have sometimes severely damaged the mangrove ecosystem, where it has been permanently transformed to another ecosystem (Smith et al., 2009). As the mangrove habitat degrades it significantly affects the biodiversity of the region. A variety of marine and terrestrial organism depends on the mangrove area for its food, breeding and use as nursery sites and shelter. Juveniles of shark species and many reef fishes prefer mangrove as their nursery sites due to the abundance of prey and provide shelter from the predators (Morrissey and Gruber, 1993). The recent study by Carugati et al. (2018) reported a loss of benthic biodiversity over disturbed mangrove area and highlighted the need to preserve the mangrove forests to maintain the functioning of a large sector of the tropical ecosystem.

An area rich in mangrove diversity is often found in the inaccessible region, and remote sensing finds its importance as the practical alternative in monitoring the mangrove ecosystem (Gupta et al. 2018). Over the last few decades, remote sensing data have provided spatio-temporal information on mangrove ecosystem, species differentiation and distribution, health and its changes (Kuenzer et al. 2011). The archived historical satellite data have facilitated the researchers to study the multi-decadal changes in the mangrove ecosystem around the world (Quader et al 2017). In the present manuscript,

we have used satellite images spanning a period from 2003 to 2017 to analyse the change in the mangrove cover with respect to pre and post 2004 Sumatra earthquake.

Study Area

The Andaman and Nicobar archipelago comprises of more than 572 scattered islands bounded by the Andaman trench to the west and by Sundra fault system to the east. The Andaman Islands are located in the torrid zone with a tropical climate, where annual rainfall is around 3000 mm. These islands are bestowed reserves of the rich biodiversity of flora and fauna. The December 26, 2004 earthquake with an epicenter off the west coast of Sumatra and the consequent tsunami have caused extensive devastation of vegetation in particular to the mangrove population along the coastal region of the Andaman Islands. Several studies have been carried out to assess the post-earthquake status of mangrove (Chatterjee et al., 2008; Sachithanandam et al., 2014; Yuvaraj et al., 2014; Roy, 2016). These studies are mostly carried along the southern Andaman Islands, which mainly focused on the impact of the tsunami. The present study is restricted to the region bounded between the geographical coordinates of $93^{\circ} 73'$ to $92^{\circ} 47'$ and $13^{\circ} 15'$ to $13^{\circ} 40'$ as shown in figure 1 and focus on the change in mangrove cover due to the earthquake and resultant uplift of the subcontinent.

Data and Methodology

Datasets Used

Cloud-free surface reflectance data of Landsat 4, 5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) of the North Andaman Islands (path number 134 and row number 51) from 2003 to 2017 has been acquired from USGS website (<http://earthexplorer.usgs.gov>). The data gap of LANDSAT during 2012 and 2013 is filled using Resourcesat-1 LISS-3 data. The list of satellite data used is shown in table 1.

Mangrove Classification

Remote sensing technology has been widely accepted as the tool for monitoring and mapping the mangrove habitat, where several methods are employed on optical imageries to classify mangrove habitats. Visual interpretation analyses and on-screen digitization has been widely used to acquire information related to the mangrove cover and its changes. Textural and spectral characteristics of the canopy are the main features used to map the mangrove cover. With the availability of free satellite data sets, with high temporal and spatial resolution, and sophisticated computation facility, Cardenas et al. (2017) argue to enhance the program skills for developing automated monitoring of mangrove habitat. Many studies are also carried out using vegetation index mainly NDVI, where

classification is done to separate vegetation and non-vegetation and mangrove and non-mangrove area.

The present study has used Combined Mangrove Recognition Index (CMRI) developed by Gupta et al. (2018). The method incorporates outputs from NDVI and NDWI indices which classify the mangrove based on its greenness and water content. CMRI is the difference between NDVI and NDWI, which assimilate the mangrove property of high water content using NDWI and the greenness using NDVI. The details and validations of the algorithm are given by Gupta et al. (2018).

The spatial coherence of CMRI estimated mangrove coverage is evaluated using the existing mangrove database under Coastal Zone Information System (CZIS) prepared for the Ministry of Environment, Forest and Climate Change, Government of India (Coastal Zone of India, 2012). CZIS database is prepared using LISS-4 data of 2004 by visual interpretation and is considered as the baseline database of the Indian coastal ecosystem.

Hydrodynamic Simulation

A tidal hydrodynamic simulation study is carried out using Telemac-2D to understand the change in the tidal influx along a creek in the northern Andaman Island after the earthquake event of 2004. Telemac-2D is an ideal modelling framework for the creek environment due to its finite element grid which allows graded mesh resolution. The model used for the simulations is 2D depth-averaged mode, based on the shallow water Saint-Venant equations of momentum and continuity, derived from the Navier Stokes equations by taking the vertical average (Hervouet, 2007).

The simulation is carried out for a selected creek along the NAI where the domain is represented by a mesh with 18666 nodes (Figure 2). The geometry of the domain is prepared using the integration of available NHO charts and ETOPO-1 data sets. Turbulent viscosity has been set constant with a viscosity (molecular + turbulent) coefficient equals to $10^{-6} \text{ m}^2\text{s}^{-1}$, while the bottom friction used is based on strickler's law of bottom friction with a constant friction coefficient of $35 * 10^{-2} \text{ m}$ is given.

The simulation of hydrodynamics under pre-earthquake scenario is carried out by forcing the domain with tidal elevation data of February 2004 from TPXO 7.0 data sets. The earthquake of December 2004 has uplifted the NAI by 1.2 m, which is evident from the uplift of Ariel jetty at NAI reported by Malik and Murthy (2005). The hydrodynamic simulation under post-earthquake scenario is carried out by raising the geometry of the domain by 1.2 m and then forcing the domain with tidal elevation data of February 2005. The number of times each element gets inundated is then computed for both the scenarios and the change in the tidal inundation under post-earthquake condition is estimated.

Results

CMRI is used to estimate mangrove cover from the Landsat data of March 13, 2004. CZIS mangrove database is used to assess the spatial coherence of the mangroves mapped using CMRI (Table 2). The mangrove layers estimated using CMRI covered a total area of about 85.9 sq. km, while the mangrove from the CZIS database cover an area of about 80.2 sq. km. Over 84 % of the CMRI estimated mangrove region is observed to overlap spatially with that of CZIS database. Figure 3 shows the comparison of CMRI estimated mangrove area and from the CZIS database for a representative region of the NAI.

Twelve major areas of mangrove cover are identified, and the temporal changes in the mangrove cover are analysed individually for these reference areas (Figure 4). The temporal changes are estimated as the changes in the mangrove pixel count estimated using CMRI.

Figure 5a shows changes in mangrove cover at region C, a representative mangrove patch along the west coast. The sequence of temporal change in the pixel count of CMRI estimated mangrove region for the region C is shown in figure 5b. Percentage of degradation of mangrove estimated is given in table 3. The reduction in the mangrove cover is observed to be disastrous as about 97 percent of the total mangrove have been lost during the period. It can be observed from figure 5a and 5b that extensive destruction of mangrove habitat has occurred during the period.

Interestingly, an immediate impact of earthquake or tsunami is not observed from the satellite images, where the number of mangrove pixel count remained above 6000 up to the early months of 2006. After that, a sudden change is observed, where the pixel count has reduced to half during December 2006. Almost a complete loss of mangrove cover is observed subsequently during 2008, where the pixel count has drastically reduced to hundreds. From figure 5a it is observed that the mangroves located to the landward side of the mudflat was the first to get affected, while those along the periphery of the tidal channel was able to sustain for a longer period and the mangrove cover fringing along the coast is observed to be unaffected.

Another representative mangrove region of the western coast (region F) is shown in figure 6a, and the change in pixel count of mangrove is shown in figure 6b. The trend in reduction of mangrove cover is similar to that of region C. The mangrove pixel count was constant to about more than 16,000 up to March 2006, which got reduced to 25 percent to around 10,000 during December 2006. The region has suffered a total loss of about 93 percent of the mangrove habitat area (Table 3). Few patches of mangroves are still observed to the landward side, which is located along the periphery of tidal channels.

Figure 7a shows the change in mangrove habitat cover at the region I along the east coast of the Northern Andaman Islands. Even though the mangrove cover area is observed to get reduced, the loss of mangrove habitat is not as intense as that observed along the regions of the western coast. The temporal changes in the mangrove cover are shown in figure 7b. The CMRI estimated mangrove cover shows a gradual decrease in the pixel count and the total loss of mangrove habitat is 41 percentage, which accounts to be the minimum for the study region.

The changes in the mangrove cover area for region J, located towards the head of Aerial Bay along the east coast is shown in figure 8a and 8b. Here also the mangrove pixel count shows a gradual decrease, with almost constant pixel count since March 2013. Even though there is a substantial reduction in the mangrove cover within the reference area, new areas of mangroves are observed to the seaward side.

The total mangrove cover estimated from 2017 image is around 21.7 sq.km out of which 1.5 sq.km of mangrove area has been newly formed. The total loss in mangrove habitat area is over 65 sq.km, which is significant to cause a regressing state of the biological ecosystem.

Numerical simulations are carried out for one month under the two scenarios of pre and post-earthquake conditions. Figure 9 shows the number of time each element in the domain gets inundated under the different scenarios. From the figure **No**, it can be seen that the mudflat towards the landward region never got inundated by the tidal flow after the December 2004 earthquake and the number of times the tidal water enters the channel have also got reduced significantly.

Discussions

An enormous area of mangrove habitat of about 65 sq.km has been lost since the 2004 earthquake. The earthquake has uplifted the islands to about 1.2 m, which have prohibited the influx of tidal currents reaching the tidal mudflats. The tidal hydrodynamic simulation results with post-earthquake conditions clearly show a significant reduction in the tidal inundation and a large area of mudflats to the landward side is observed to be devoid of any tidal inundation. This reduction of the tidal currents because of the altered geomorphology of tidal channels can be attributed to the significant loss of mangrove habitat, since tide plays a vital role in mangrove growth through nutrient distribution, waste removal, maintaining geomorphology and preventing competition by excluding terrestrial vegetation.

It is observed that the mangrove habitat located to the west coast of the NAI have incurred severe damages than those located to the east coast. The islands have uplifted with a tilt which slopes towards the east and could be the probable reason for the difference in the intensity of mangrove

habitat regress between the western and eastern coast of the island. A total loss of mangrove habitat is observed to the west coast where only a few patches of mangroves located to a narrow band of coast region and tidal channels have sustained, while for the eastern mangrove regions, the loss of mangroves is only along the regions located further landward from the sea.

Observations of the temporal changes in the pixel count of CMRI estimated mangroves indicates that there was no immediate effect of earthquake or tsunami on the mangrove habitat. The period of 15 to 20 months after the earthquake through which the mangrove habitat was intact can be considered as the limiting period for the mangrove species where it can sustain under the condition of deprived tidal currents.

A close observation of the figure 5-8 shows that a large portion of the initial mangrove cover region has changed to the non-vegetated area and subsequently to other vegetation. This change from non-vegetated area to other vegetation is prominent along the mangroves located to the eastern coast, while at the mangrove area to the western coast, larger areas have remained under the non-vegetated category. This implies that the terrestrial vegetation is observed to grow along the mudflats which were once excluded from its growth due to the frequent inundation of tides. The coastal geomorphology as well the plant demography has changed significantly since the cease of tidal inundation due to the coastal uplift.

New patches of mangroves are observed to grow towards the sea region, specifically at region J. The mangrove growth is observed over the new land that has emerged due to the uplift, and the area of mangrove growth is estimated to be around 1.5 sq.km. Why new patches of mangroves are only observed in region J may be an intriguing question. However, the landform of the emerged substrate may be the reason for the new mangrove growth to be restricted at region J. The earthquake has resulted in the exposure of coral bed (Malik and Murthy, 2005) along the main shoreline, whose hard substrate prohibits the growth of mangrove. Unlike the other mangrove area, the region J is located away from the main shoreline and towards the head of Aerial Bay, which may have sufficient deposition of mud materials. The earthquake might have exposed these mud depositions with a porous substrate where mangrove growth can be possible.

Conclusions

The use of satellite images and indexing methods ease the job of estimating the temporal changes, specifically for habitats like mangrove which are inaccessible for ground observations.

The interesting aspect of the present study is to substantiate how natural processes can induce irrecoverable changes in the ecosystem. The loss of mangrove forest is about 75 percent of the

estimated 85.9 sq.km of the mangroves grown along the northern Andaman Islands during pre-earthquake. This loss of mangrove forest is observed not to be a spontaneous impact of earthquake or tsunami, but a gradual and permanent one. The mangroves are observed to be intact for more than 15 months after the tides have desisted to inundate the mudflats.

The study specifically assents the importance of tidal water for the sustainability of mangrove habitat. As the seawater ceased to inundate the mudflats during high tidal condition due to the land uplift, the bio-geo-chemical conditions of the substrate have undergone a substantial transformation which is presumed to create hostile conditions for the mangrove to sustain its growth. Tides help in the mangrove growth by the exclusion of other vascular plants, distribution of nutrients, flushing out the salt and other wastes. Tides also help in maintaining the geomorphology of the region by making the substrate porous for the nourishment of mangroves and its reproduction. Simulation of the tidal hydrodynamics shows that, after the earthquake, there are large areas of the mudflat which has never been inundated with the tide and other regions shows a significant reduction in the frequency of inundation. This reduction in the tidal inundation is an immediate consequence of the earthquake due to the coastal upliftment, while deterioration of the mangrove habitat has certainly lagged for more than a year.

The degradation of the mangrove cover is severe and extensive that it may have a large and prolonged impact on the biological ecosystem. Mangroves form at large a vital habitat for a variety of marine and terrestrial organism, while it also provides shelter and acts as a feeding ground for the juveniles of larger predatory fishes. The loss of mangrove habitat is estimated to be around 65 sq. km, which can crucially alter the entire system of ecological balance within a larger extended area.

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Table 1: List of satellite data used

Date	Satellite
December 8, 2003	LANDSAT 5
March 13, 2004	LANDSAT 5
February 12, 2005	LANDSAT 5
March 3, 2006	LANDSAT 5
March 6, 2007	LANDSAT 5
March 24, 2008	LANDSAT 5
March 11, 2009	LANDSAT 5
February 26, 2010	LANDSAT 5
February 13, 2011	LANDSAT 5
February 11, 2012	Resourcesat-2
March 13, 2013	Resourcesat-2
March 09, 2014	LANDSAT 8
March 12, 2015	LANDSAT 8
March 14, 2016	LANDSAT 8
March 17, 2017	LANDSAT 8

Table 2: Comparison of CMRI estimated mangrove with CZIS database

CZIS area	80.20 sq. km
CMRI area	85.91 sq. km
Overlap area	72.33 sq. km
Area under error of omission	8.06 sq.km
Area under error of commission	13.57 sq.km

Table 3: Mangrove cover change over the period of study

Mangrove Region	Initial pixel count	Pixel count 2017	Percentage loss of mangrove cover
A	3107	178	94.27
B	4085	374	90.84
C	6311	143	97.73
D	1368	7	99.49
E	2937	46	98.43
F	16871	1085	93.56
G	1814	39	97.85
H	2883	82	97.15
I	14727	8570	41.8
J	8403	2328	72.30
K	14347	5138	64.19
L	9235	2828	69.37

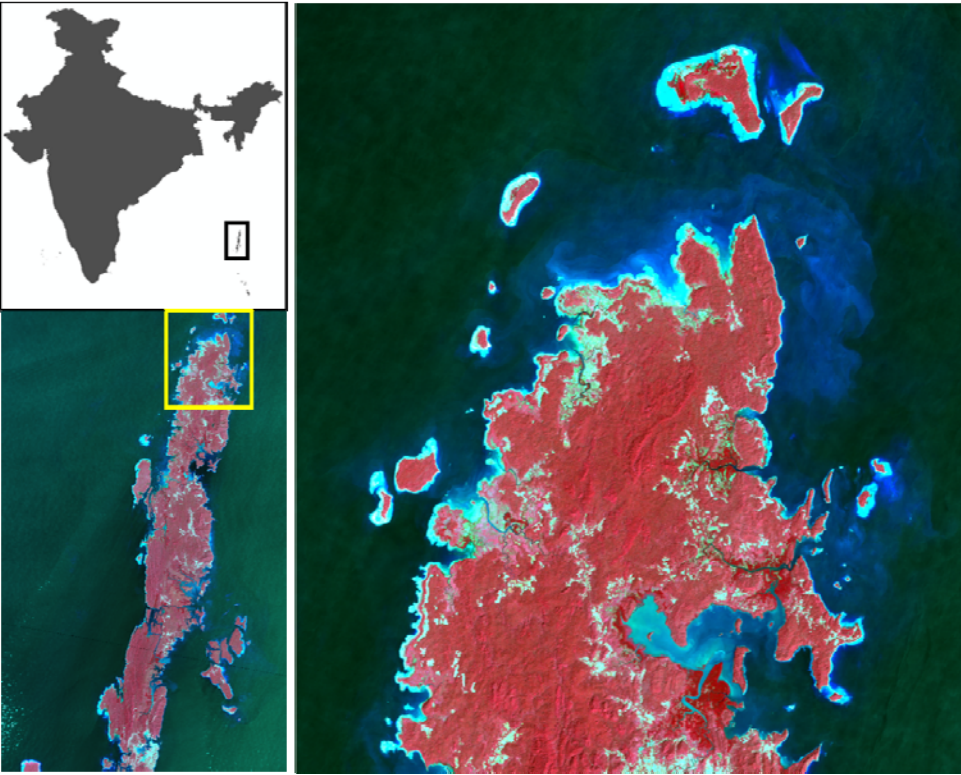


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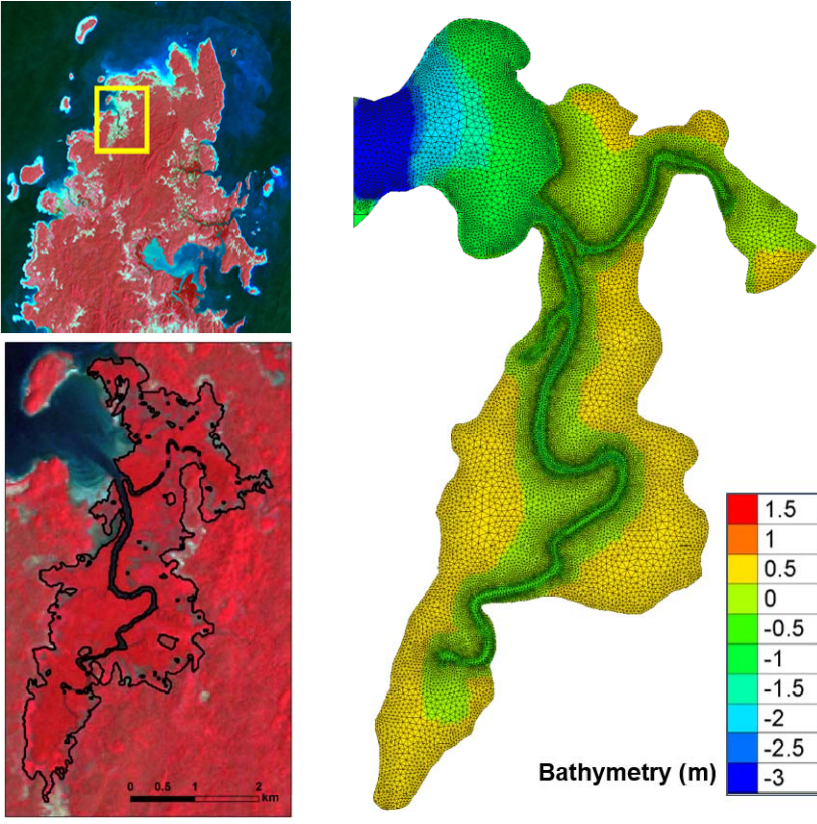


Figure 2: Bathymetry overlaid with grid for the selected mudflat along the Northern Andaman Island

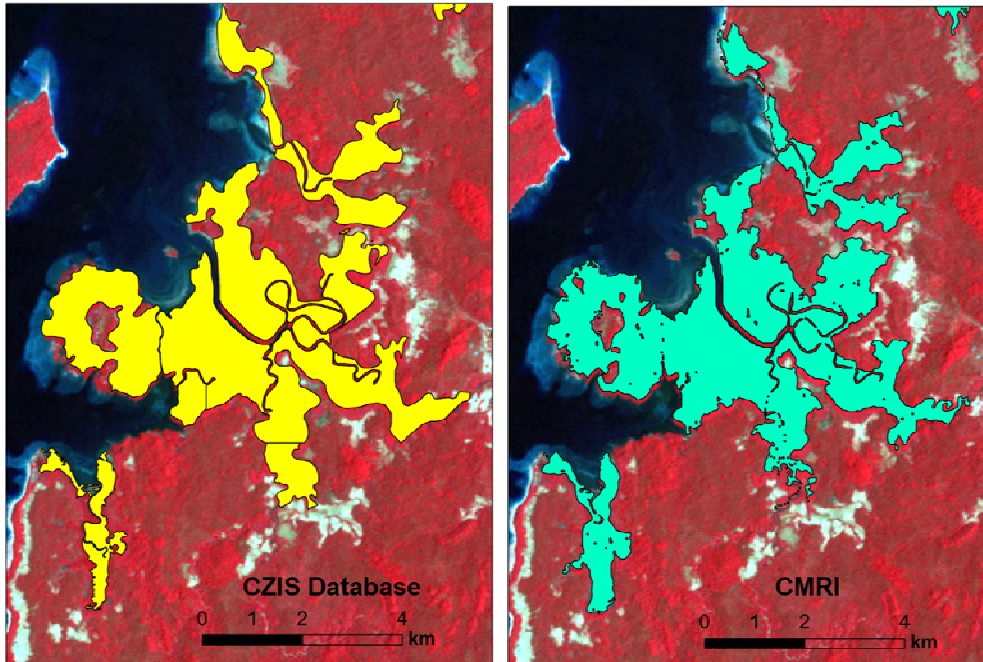


Figure 3: Comparison of CMRI estimated mangrove cover with existing CZIS database for a selected region of mangrove along the west coast of NAI

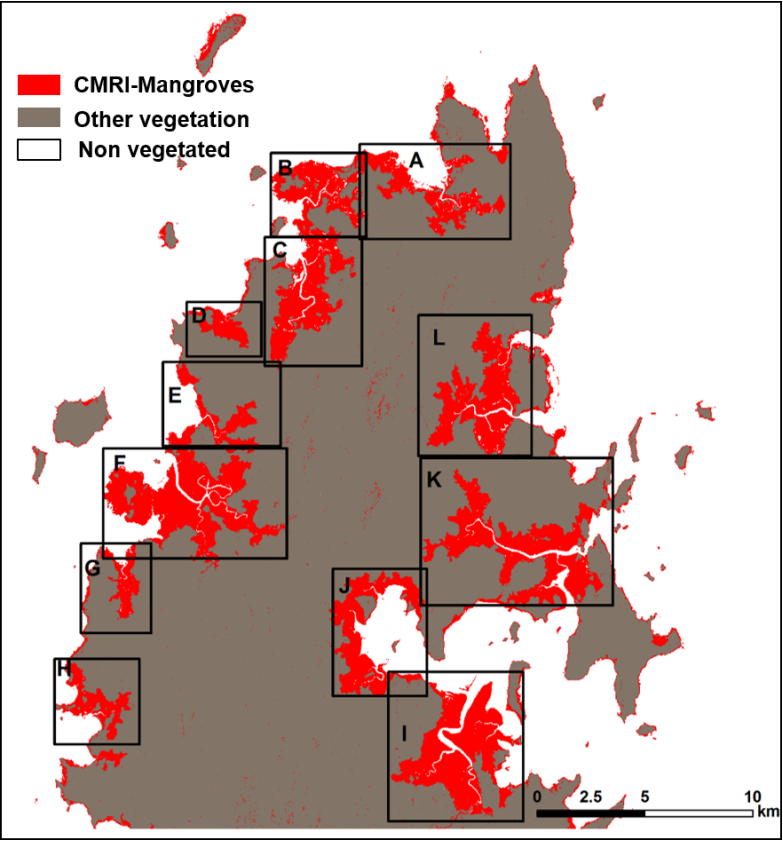


Figure 4: CMRI estimated mangrove area, the inset boxes shows the major mangrove cover regions

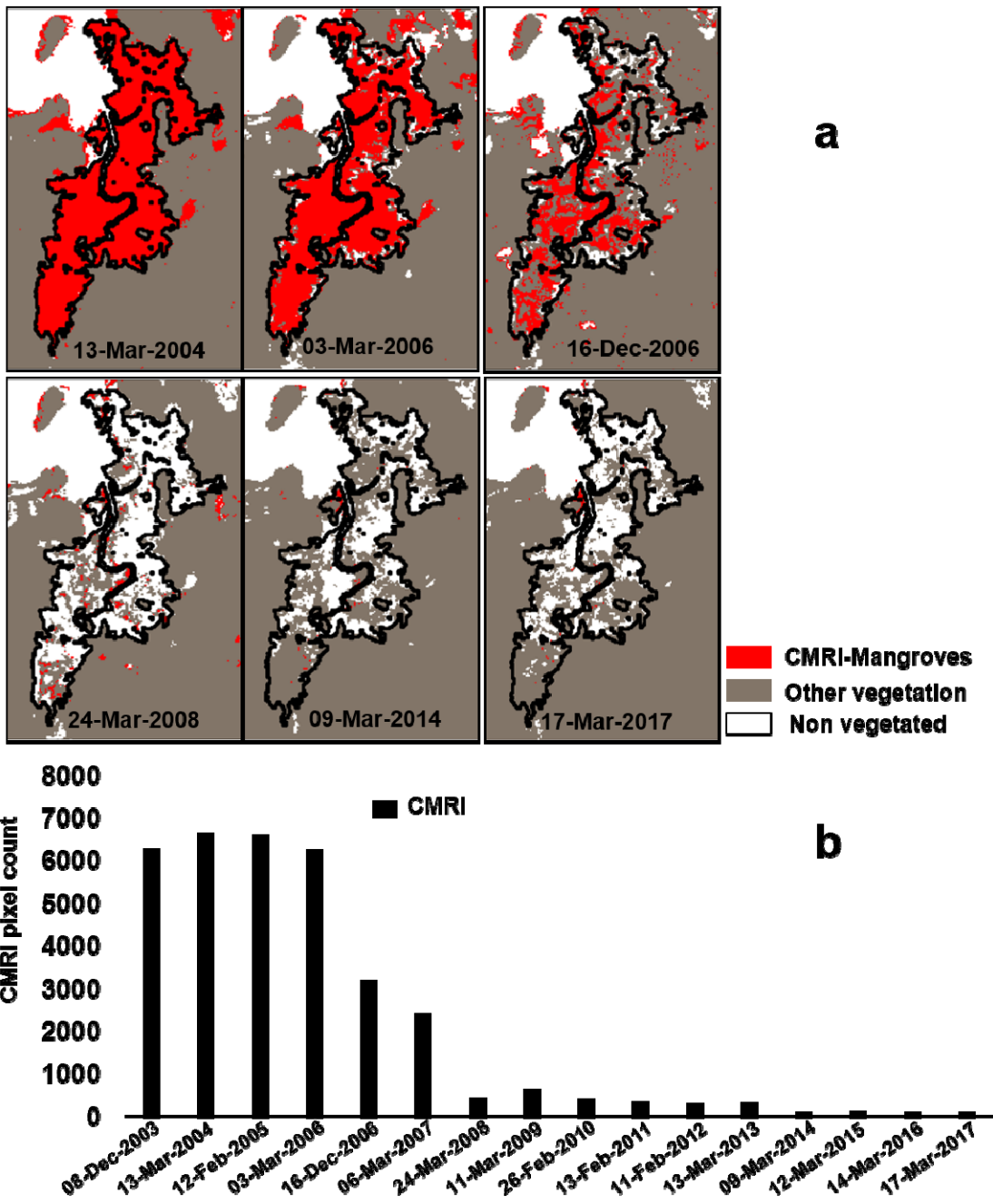
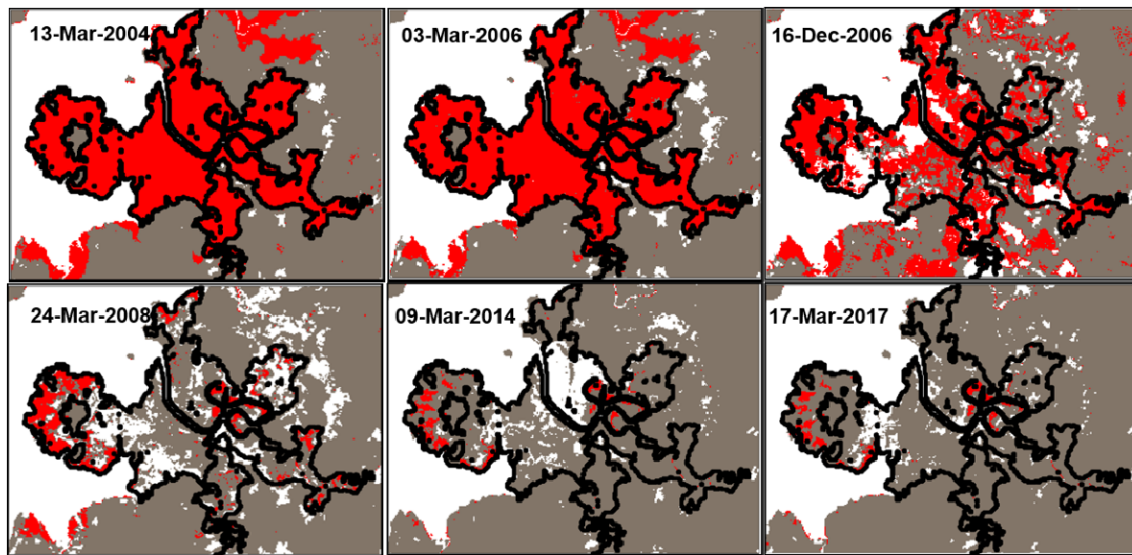
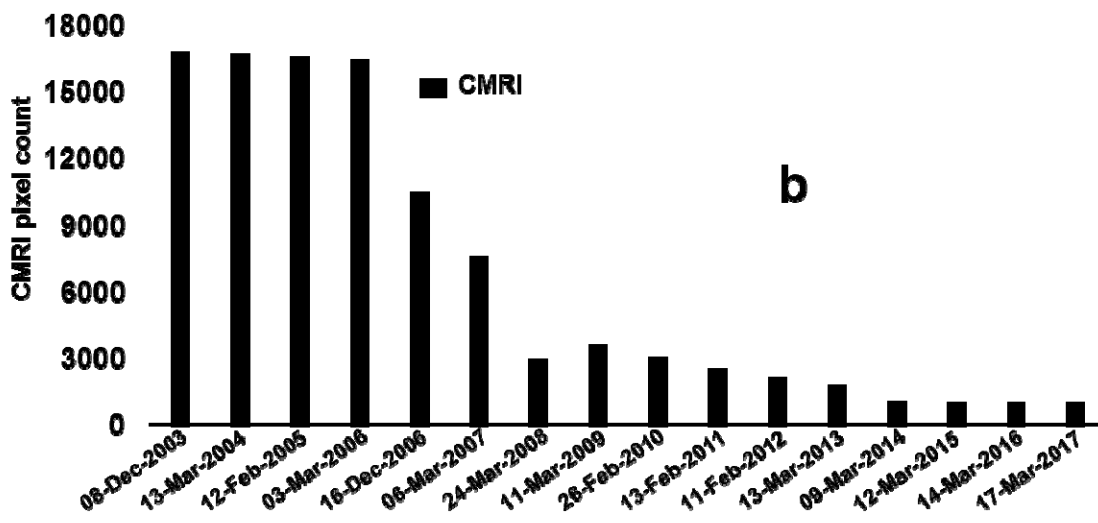


Figure 5: a) Temporal changes in the mangrove cover for area C, b) temporal changes in the CMRI estimated mangrove pixel count



a

- CMRI-Mangroves
- Other vegetation
- Non vegetated



b

Figure 6: a) Changes in the mangrove cover for area F b) temporal changes in the CMRI estimated mangrove pixel count

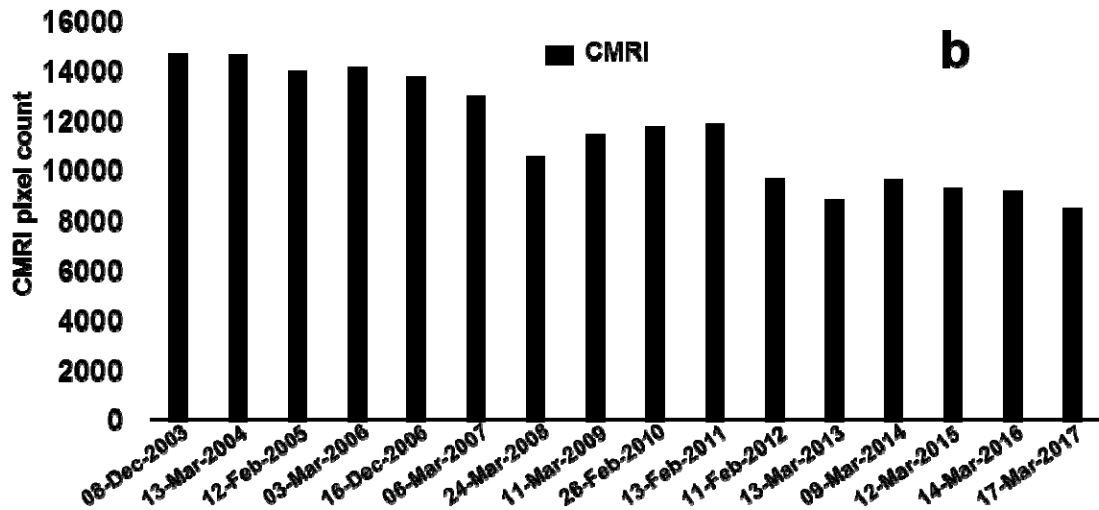
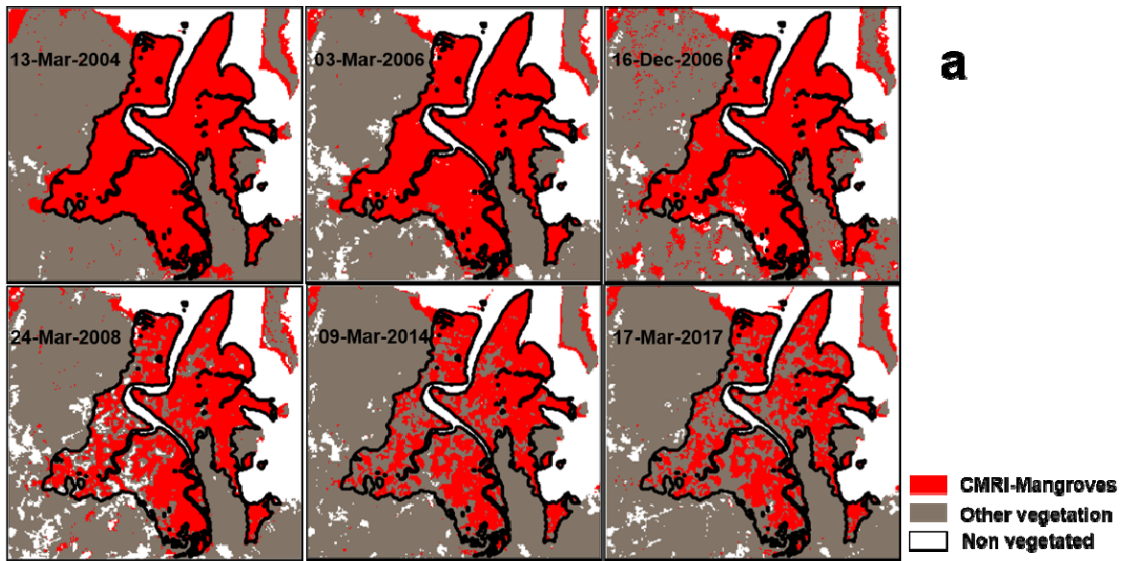


Figure 7: a) Change in mangrove cover for area I, b) temporal changes in the CMRI estimated mangrove pixel count

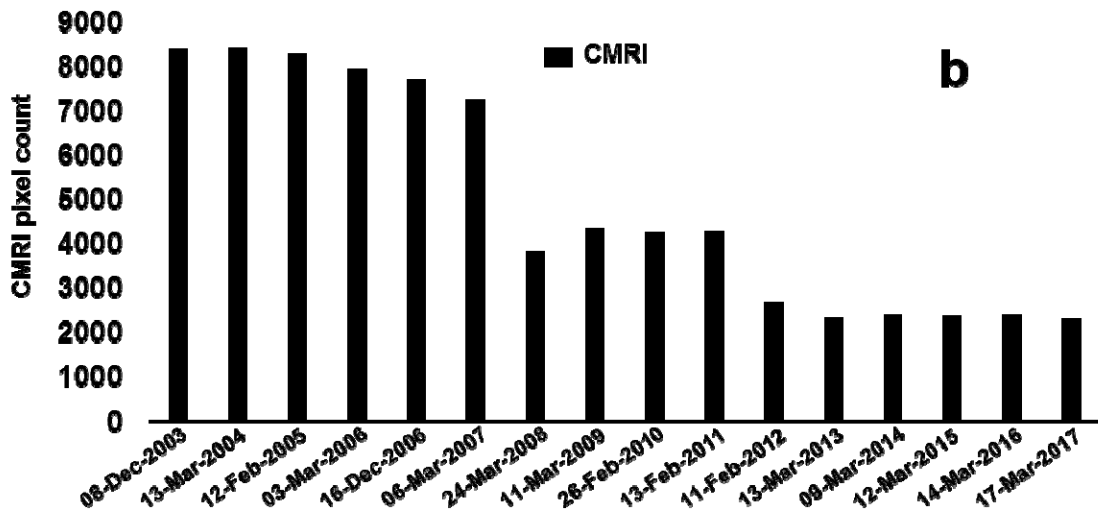
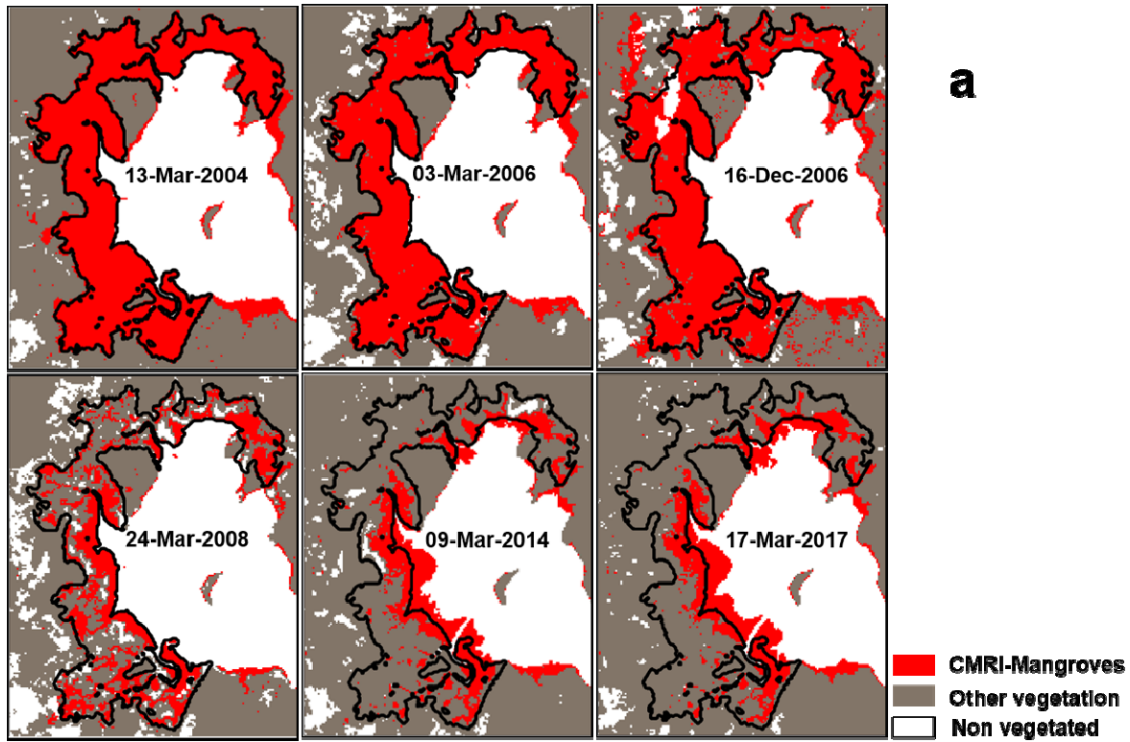


Figure 8: a) Changes in mangrove cover for area J, b) temporal changes in the CMRI estimated mangrove pixel count

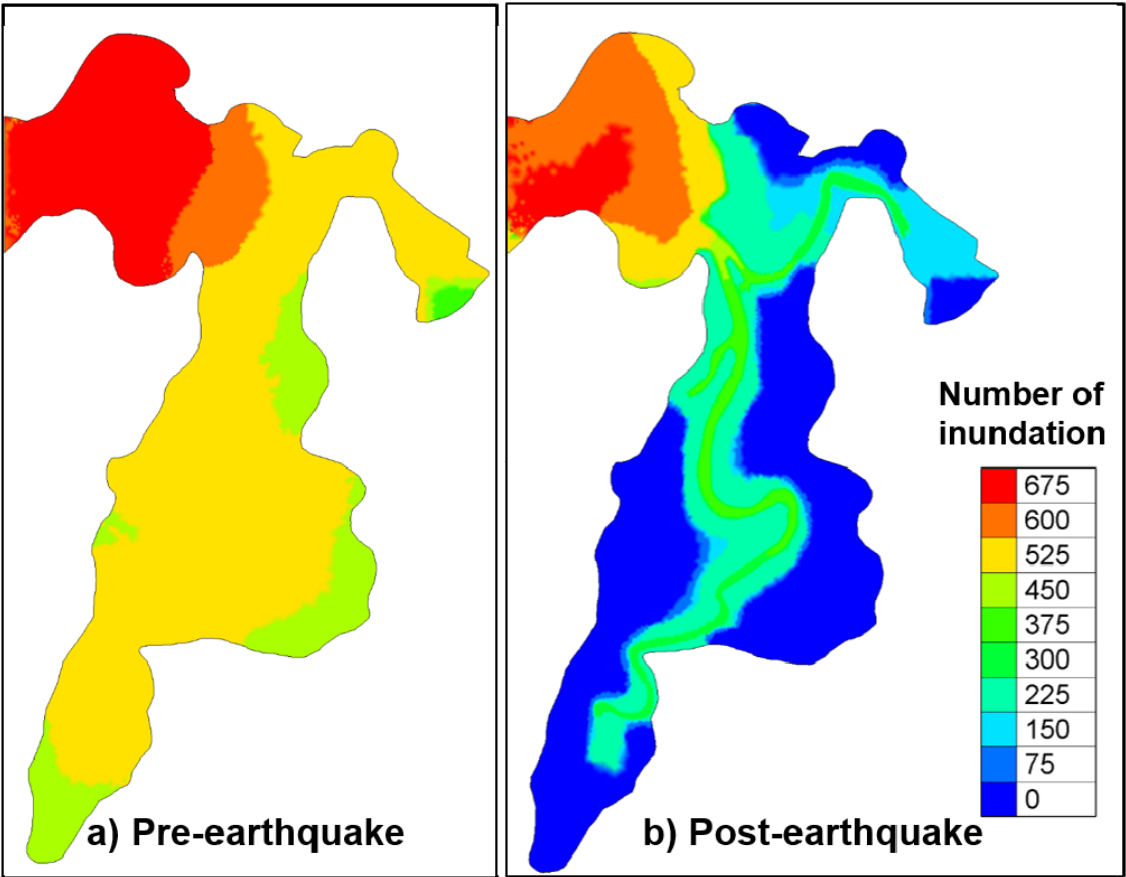


Figure 9: Simulated inundation scenarios under a) pre-earthquake and b) post-earthquake conditions