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Assessing the impact of the 2004 tsunami on mangroves using remote sensing and GIS techniques

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While tsunami characteristics and effects are not fully understood in the countries around the Indian Ocean, there are reports suggesting that mangroves, acting as a barrier, significantly reduce the devastation caused by the waves. This study proposes a creative approach to investigating the impact of the 2004 tsunami on mangrove vegetation. The approach involves a combination of Geographic Information System (GIS) proximity analyses and change detection methods in remote sensing to delineate multiple buffer distances from the coastline into four homogeneous subregions. The changes in land cover are then assessed in these subregions before and after the tsunami event. The proposed approach provides a more reliable and accurate means than conventional methods to evaluate spatial patterns of damaged areas through different land characteristics along the coastline. There are major damages to land cover, representing an average of 26.87% change, in those geographic locations with low mangrove coverage that are in close proximity to the coastline in all four subregions, whereas less damage is apparent in locations with high mangrove coverage, representing an average of only 2.77% change. The optimum distance between 1000 and 1500 m of mangrove buffer would be favourable and most effective for reducing the damage by potential tsunami waves. The findings support the need for mangrove replantation and management in the future and may serve as a prototype for studying impacts of tsunamis in other affected countries.

1. Introduction

Tsunamis had never occurred before in the Indian Ocean, yet in 2004 a very powerful earthquake with a magnitude of 9.3 on the Richter scale, the world’s largest earthquake since the Alaskan event of 1964, landed off the coast of Sumatra. The shock created a powerful tsunami that killed more than 200,000 people and affected millions on 26 December 2004 (Baumann 2005, Kathiresan and Rajendran 2005). This tsunami was triggered as a result of a series of very long waves generated from a very powerful earthquake. Since 1750, the Indian Ocean has not experienced a natural disaster of such magnitude, with enormous consequences for the region’s environment (O’Neil 2005). Thus, it is important to understand how to react and

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prepare for this kind of disaster in the future. For the long-term environmental benefits, scientists have a key interest in understanding the role of natural resources, such as mangroves, in reducing the impact of tsunamis (UNEP 2005). The fundamental role of coastal vegetation, together with the location characteristics of human inhabitation, should be fully investigated to establish potential benefits, especially how they protect lives and wealth from a tsunami. This study proposes a creative approach to investigating the impact of the 2004 tsunami on mangrove vegetation. The approach involves a combination of Geographic Information System (GIS) proximity analyses and change detection methods in remote sensing to delineate multiple buffer distances from the coastline into four homogeneous subregions. The changes in land cover are then assessed in these subregions before and after the tsunami event. Using this approach, we tested two hypotheses: (1) a densely populated mangrove can reduce the damage caused by the tsunami waves; and (2) the further the distance of the mangrove from the coastline, the less the severity of the damage caused by the tsunami waves.

Mangroves are one of the most important ecosystems in wetlands, with a high biodiversity. Mangroves are defined as woody plants, basically found throughout the world in tropical and subtropical areas (Chapman 1976). They have well-known characteristics, such as exposed breathing roots and foliage salt excretion. The spatial distribution of mangroves is limited by the physiological tolerance of each species to low temperature (Duke et al. 1998). Some can survive air temperatures as low as 5°C, high salinity, extreme tides, strong winds, and even muddy anaerobic soil conditions. However, mangroves are intolerant of frost and prefer a warm, humid climate and freshwater inflow that brings in fertile nutrients to support more diverse communities (Tomlinson 1986, Duke 1992, Ellison et al. 1999, Hogarth 1999, Kathiresan and Bingham 2001). Because of the influence of precipitation and temperature, 90% of the world’s mangroves are found in warm humid areas or tropical summer rainfall regions (Blasco 1984). Nevertheless, mangrove habitats have relatively low floristic species richness compared to other tropical habitats such as coral reefs and rain forests (FAO 1982, Ricklefs and Latham 1993, Ellison et al. 1999).


Both at local and global levels, mangrove forests play a fundamental role because they are an important source for wood production, food resources and land protection (Blasco 1975, Robertson and Alongi 1992, Pearce 1999). They offer shoreline protection by acting as a greenbelt, protecting seaward habitats against influences from the land and, more importantly, protecting landward coastal areas against influences from the ocean (Dahdouh-Guebas 2006). Following a hydraulic experimental design, Harada et al. (2002) established the role of mangroves as an effective barrier in serving as seawall structures that may reduce the effects of tsunamis on human dwellings and coastal landforms. A study by Mazda et al. (2002)
on the impact of wave reduction in a mangrove reforestation area in the Tong King delta in Vietnam showed that when water depth increases, the effect of wave reduction does not decrease in a well-grown mangrove area. The study observed a rate of wave reduction per 100 m in the tall mangrove areas as large as 20%, thus demonstrating the usefulness of mangrove forests for shoreline protection from wave erosion. A study by Kathiresan and Rajendran (2005), immediately after the December 2004 tsunami event, demonstrated the role of mangroves in mitigating the effect of the tsunami and observed that geographic locations with mangroves tolerated the waves without showing apparent damage while most of the other coastal vegetation was destroyed. Therefore, preservation of mangrove forests is useful because they not only maintain the stability of the existing tropical ecosystem but also indirectly provide protection to coastal communities.

The compilation of baseline map data can be achieved using remote sensing and GIS technologies. In the past decade, remote sensing and GIS have been very useful in providing spatial information at various scales in coastal zones. Several studies have reported the effectiveness of using remotely sensed data and GIS as a powerful tool to detect land use/land cover change, land use/land cover mapping, urban planning, vegetation mapping, and hazard mapping (Salas and Brunner 1998, Hurd et al. 2003, Sun et al. 2003, 2005, Jiang et al. 2004, Saha et al. 2005). Advanced manipulation of remote sensing data in combination with GIS techniques could play a significant role in coastal zone research, providing quality, timely and cost-effective data (Hardisky et al. 1986, Klemas 2001, Nayak 2002, Oyana 2004). For example, remotely sensed data can be used effectively for rapidly assessing the severity and impact of damage due to a natural disaster, planning escape routes, locating shelters for victims during the disaster, identifying hardest-hit disaster areas to provide warning and evacuation, and monitoring reconstruction and rehabilitation after the disaster (Nirupama 2002). Remote sensing applications in mangrove management are usually used for three main purposes: resource inventory, change detection, and the selection and inventory of aquaculture sites (Green et al. 2000).

Many studies in the past decade have been carried out on mangrove forests, such as mangrove mapping or monitoring, using remote sensing and GIS (Held et al. 2001, Hosking et al. 2001, Proisy and Mougin 2001).

2. Study area

Thailand is one of many tropical countries with a large area of mangrove forests, with 927 km of mangrove line (FAO 1985). The best developed mangrove forests in Thailand occur on the west coast of the peninsula in Phang Nga, Ranong, Trang and Satun. Unfortunately, Thailand’s mangroves are under increasing pressure, and some have been destroyed and threatened by various forms of human activities. The major reasons for changes in the mangrove forests in Phang Nga are mangrove forest concessions, shrimp farming, coastal development and tin mining, all of which have led to the degradation and ecological disturbance in these mangrove areas (Charuppat and Charuppat 1997, Sremongkontip et al. 1997, Plathong and Sitthirach 1998). In Thailand, mangrove forest areas declined from an estimated 367 000 ha in 1961 to 168 682 ha in 1993 (Boonsong and Eiumnoh 1995). Mangrove areas in Phang Nga, the study area, have been reported in the study by Plathong and Sitthirach (1998) to have decreased from 57 400 to 38 137 ha during 1961–1996. Phang Nga mangroves are dominated by Rhizophora species, which has the most remarkable adaptations of its root system. The specialized root system is highly
adapted to the coastal environment, not only providing an important site of gas exchange for mangrove living in anaerobic conditions but also binding marine and terrestrial sediments as a defence against the power of tropical storms and ocean waves (Ruitenbeek 1992, Janssen and Padilla 1999, Kathiresan and Bingham 2001).

Phang Nga province is located in the southern part of Thailand on the Andaman coastline within latitudes 9.32° N and 8.13° N and longitudes 98.39° E and 98.40° E. The study area, as illustrated in figure 1, covers an estimated total area of 2000 km². The province has assorted land use characteristics with large portions of mixed vegetation, barren land, agricultural area, and beaches. Phang Nga is one of the world’s most famous destinations for tourists, featuring numerous infrastructures, densely constructed along the shorelines of the province, such as houses, hotels, resorts, restaurants and highways. The major reasons for changes in the mangrove forests in Phang Nga are urban developments to build hotels, roads and resorts, mangrove forest concessions, tin-mining activities, and intensive shrimp farming, all of which have led to the degradation and ecological disturbance in the mangrove areas. According to preliminary reports, Phang Nga province was the worst-hit coastal province from the tsunami (Tingsanchali 2005, UNEP 2005).

3. Datasets and methods

In this study, we have developed a creative approach using several procedures of image analysis and interpretation, and change detection techniques in remote sensing, in combination with GIS proximity analyses to investigate the impact of the 2004 tsunami on mangrove vegetation. Land cover changes were assessed using

Figure 1. Location of study area, Phang Nga Province.
satellite images taken before and after the tsunami event. These were achieved by delineating multiple buffer distances from the coastline as four homogeneous subregions. For image analysis and change detection processes, hybrid land cover classification and cross-tabulation change detection techniques were used, respectively, to determine the effect after the tsunami. The approach was implemented using ERDAS IMAGINE 8.7 (Leica Geosystems GIS & Mapping LLC, 2003), combined with ArcGIS 9.0 (ESRI, 2005) and IDRISI 32 (Clark Labs, Worcester, MA, USA).

3.1 Description of datasets

Landsat imagery was used as the primary data source together with aerial photographs, high-resolution IKONOS imagery and a topographic map to enhance quality of analysis. Satellite imagery at two different dates, obtained from Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper Plus (ETM+), were used for determining the changes in land characteristics caused by the tsunami in the study area.

Landsat imagery data incorporate six different spectral bands 1 (blue), 2 (green), 3 (red), 4, 5 and 7 (near- and mid-infrared), and exclude the thermal band of band 6 due to course spatial resolution. Landsat ETM+ digital data (path/row: 130/54) of 15 January 2002 and Landsat TM digital data (path/row: 130/54) of 30 December 2004 were used to represent data pre- and post-tsunami. These images are in the Universal Transverse Mercator (UTM) Zone 47 coordinate system, Spheroid WGS 84, and Datum WGS 84.

At the time of conducting this study, it was not possible to incorporate groundtruthing field data. Instead, sets of aerial photographs covering the coastal area of the study area were scanned and processed for accuracy assessment. Table 1 presents a list of the reference data used in this study. IKONOS provides a high-resolution image and was used to acquire ground control points instead of groundtruthing field data.

In additional, a 1985 topographic map of scale 1:250 000 obtained from the Royal Thai Survey Department was scanned as a reference map. This map was used for image registration and to acquire elevation data for the study area.

3.2 Image analysis methods

The major components of the proposed approach included image pre-processing, image classification, accuracy assessment, image separation, GIS proximity analysis, change detection, and analysis of spatial distribution and association of land cover changes to illustrate the impacts of the tsunami on the mangroves and surrounding areas. The two Landsat images used in the change detection were taken on 15 January 2002 and 30 December 2004, which are about 2 weeks apart in terms of

<table>
<thead>
<tr>
<th>Data</th>
<th>Acquisition date</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black and white aerial photographs</td>
<td>4 January 1999</td>
<td>1:50 000</td>
</tr>
<tr>
<td>Colour aerial photographs</td>
<td>15 January 2005</td>
<td>1:15 000</td>
</tr>
<tr>
<td>Topographic map</td>
<td>1985</td>
<td>1:250 000</td>
</tr>
<tr>
<td>IKONOS images</td>
<td>29 December 2004</td>
<td></td>
</tr>
</tbody>
</table>
monthly tidal effects. Therefore, the tidal effects in the study area should be very similar and were considered to be negligible for multitemporal analysis. Figure 2 illustrates graphically the methodological processes used in achieving the goals of this study.

3.2.1 Image pre-processing. When conducting change detection between two or more dates of remote sensing data, it is necessary to select an approach involving either image-to-map or image-to-image registration (Jensen 2005). The pre-tsunami image was first registered to the topographic map at a 1:250,000 scale. The post-tsunami image was then registered to the pre-tsunami image. These data were resampled using the nearest-neighbour resampling technique as no change occurs to the pixel values.

3.2.2 Hybrid classification. Hybrid classification was performed by combining an unsupervised ISODATA and a supervised maximum likelihood algorithm (Sun 2004). The classification is hybrid in that signatures used to perform supervised

![Figure 2. A graphic illustration of a spatial model that combines GIS, remote sensing and statistical techniques to investigate the impact of the 2004 tsunami on mangrove vegetation.](image-url)
classification are generated from both the ISODATA clustering procedure and the training samples. The hybrid method is different from supervised classification because in the latter case, signatures are obtained only from training samples. The hybrid method also differs from unsupervised classification, in which case spectral classes are automatically detected and no training samples are involved. The hybrid classification procedure developed in this study consisted of five steps (figure 3).

1. For both pre- and post-tsunami images, unsupervised ISODATA was first applied to generate spectral classes. A set of signatures was obtained for each of the pre- and post-tsunami images. All signatures were then evaluated and assigned proper meaning or class names. This was performed by comparing the original image and available reference data with individual spectral classes. It is important to note that not all signatures obtained from the ISODATA approach were included in the final file of signatures for the supervised classification that follows (see step 4 below). Only those signatures that corresponded to clearly identified land cover types were selected and included.

2. User-defined training samples were identified and separately delineated to obtain additional signatures of land cover types for both pre- and post-tsunami images. Training samples were selected so that they were distributed evenly across the study area. To generate representative signatures for each land cover type, we repeatedly selected training samples and evaluated the signatures. This involved adding, merging and/or deleting the signatures.

3. We constructed final signature files for both pre- and post-tsunami images by combining those signatures generated from unsupervised ISODATA approach and those from the training samples obtained in steps 1 and 2.

![Figure 3. The procedure for hybrid classification.](image-url)
4. The maximum likelihood algorithm was applied to the final signature files to obtain the hybrid classified images of both pre- and post-tsunami images. The classified images are also called thematic maps.

5. We finally recoded spectral classes of the thematic map to reduce the number of classes, and labelled the classes for subsequent analysis.

3.2.3 Accuracy assessment. Because of the limitations of field surveys, several studies have recommended the use of higher spatial resolution remotely sensed data, such as aerial photographs, for ground reference information (Jensen 2005). The availability of aerial photographs for the study area facilitated the groundtruthing process for evaluating the accuracy of the classified images. We used ERDAS Imagine software to perform image classification and accuracy assessment.

It is important to note that the reference pixels used to assess the classification accuracy in this study were different from the pixels used to train the classifier. Reference pixels used for the accuracy assessment were selected after the classification using an equalized random sampling method. ERDAS Imagine automatically selected reference pixels on the scanned aerial photographs. In the equalized random sampling method, each class has an equal number of random reference pixels.

These reference pixels were then compared with those corresponding pixels on the classified images obtained from the hybrid image classification. To better visualize each type of land cover, we chose a different band combination. For example, a Landsat satellite image with a band combination of 4–5–3 (R–G–B) was used to identify the mangrove area (Sremongkontip et al. 1997).

Assessing the accuracy of class change detection is essential for subsequent analysis. A simple method was used for this purpose, which multiplies the individual class accuracies on pre- and post-tsunami classified maps to estimate the accuracy of the change map. This method was selected because it is easy to implement and does not require additional ground truth information.

3.2.4 Image separation and GIS proximity model. Because of the heterogeneity of the land cover classes and the biodiversity of the study area, we separated the study area into four regions: North, Mid, Upper-South, and Lower-South (figure 4). Each region represents distinctive land cover and geographical characteristics.

Because we considered the tsunami damage only to the land ecosystem, the coastline of the study area was digitized on-screen by using the classified pre-tsunami image as a reference coastline. This coastline was used to construct the ocean polygon. Six multiple buffer rings of 500 m up to 3000 m in varying distances were created; each buffer ring covered an area within a distance of 500 m from the previous ring, as illustrated in figure 5. A single polygon covering the entire area of the ocean was also created using the coastline of a 2002 Landsat image. The buffer rings and ocean polygon were used to clip classified images and extract areas of interest for further analysis. As each buffer ring and the ocean polygon are in the vector formats, in order to successfully clip the classified images, which are also in raster formats, the Extract by Mask Function in the Spatial Analyst extension was used. This function extracted the cells of a raster that corresponded with the areas of interest as defined by the mask. The extracted values of the raster pixels from each different buffer distance were generated and saved in a separate file as input for the change detection analysis.
Figure 4. Delineated subregions derived from image separation of the study area.
3.2.5 Change detection. Change detection provides a quantitative analysis of two classified images and the method was used to assess temporal changes in land cover before and after the tsunamis. The method was applied to assess different land characteristics from the inputs of the two temporal images resulting from the GIS.
proximity analyses. To conduct the change detection analysis, the raster images of each specific buffer distance were exported to perform cross-tabulation manipulation using IDRISI software. It was assumed that the two sets of classified images represented the temporal changes and they were compared separately. A pre-tsunami buffered area was selected as the first image and the post-tsunami buffered area was selected as the second image for comparison. The cross-tabulation function was engaged to generate matrix tables, which numerically summarized land cover changes and characteristics of the two sets of images. The visual display of the outputs showed the results in the form of colour maps, where each colour uniquely represented a change from one class to another. By analysing these matrix tables further, we were able to detect any apparent changes within the pixels of different land cover classes.

3.2.6 Impact analysis of tsunami on mangrove. During the tsunami, sand was swept from the ocean onto the land, resulting in a larger number of sand areas in 2004, while destroyed buildings and debris generally showed up as barren land on the classified images; therefore, we considered newly formed sand and barren land areas to represent damaged areas as a result of the tsunami. The data from the cross-tabulation were used to compute the percentage of damaged areas using equation (1). The ocean area was first eliminated from the analysis by subtracting the number of ocean pixels from the matrix table. We then calculated the total number of pixels showing land cover changes from other classes to barren land or sand without considering any transformed areas. This was then divided by the total number of all pixels on the images to obtain the percentage of damaged areas.

\[
P_{\text{damage}} = \frac{\sum_{i=1}^{n} C_{i \rightarrow \text{barren}} + \sum_{i=1}^{n} C_{i \rightarrow \text{sand}} - C_{\text{sand} \rightarrow \text{sand}} - C_{\text{sand} \rightarrow \text{barren}} - C_{\text{barren} \rightarrow \text{barren}} - C_{\text{barren} \rightarrow \text{sand}}}{\sum_{i=1}^{n} \sum_{j=1}^{n} C_{i \rightarrow j}}
\]

where \(P_{\text{damage}}\) is the percentage of damaged area, \(n\) the number of classes, and \(C_{i \rightarrow j}\) the number of pixels changed from class \(i\) to class \(j\).

3.2.7 Bivariate analysis of impacted areas. The idea of delineating the study region as buffer rings (subsets) was inspired by the key work of Fritz and Borrero (2006), who conducted a significant field survey after the December 2004 Indian Ocean tsunami. Earlier work by Ward and Asphaug (2002) on the impact of tsunamis provided additional understanding of the impact cavities in relation to the distance from the ocean.

Each buffer ring in the study region was assumed to be independent of the others and preliminary statistics supported our initial assumption. We were also motivated to investigate spatial relationships and differences in each category using \(\chi^2\) statistics following examples from previous studies (Heywood 1991, Sperduto and Congalton 1996, Wear and Bolstad 1998, Waite et al. 2004, Blewitt et al. 2006). In one study, Dahdouh-Guebas (2006) noted that spatial damage was not linked to geographic position in view of the tsunami wave energy.

A \(\chi^2\) analysis was conducted to analyse spatial relationships between impacted and non-impacted tsunami areas so as to statistically determine the role of mangrove vegetation as a barrier. Through cross-tabulation (change detection) and impact analyses, we established geographic locations with low and high mangrove coverage using land cover data. The data were used to construct bivariate tables for each region.
based on geographic proximity data generated from the six buffer distances. We then conducted two $\chi^2$ analyses on the spatial distributions of low and high impacted areas.

In the first analysis, we investigated whether there were spatial relationships between locations that were heavily impacted and those that were lightly impacted in the study region, and in the second analysis, we compared the impact of the tsunami on locations that were in close proximity to the coastline (within 500 m) to those that were further away. For this analysis, we assumed that the first buffer ring represented the immediate zone of the tsunami impact, and by comparing this with the others, we could empirically establish the role of the mangrove vegetation as a barrier.

4. Results and analysis

4.1 Image classification

Fifty spectral classes in pre- and post-tsunami images were generated from ISODATA for the unsupervised classification and these 50 classes were then assigned actual class names through visual comparison with aerial photographs and IKONOS scenes. It was found that water, vegetation, mangrove and barren land classes were very well identified. Therefore, spectral signatures of these classes were included in the final signature files. Additional signatures, especially signatures for sand, urban and cloud classes, were identified from training samples.

The final signature files used to train the classifier contain 60 spectral signatures and 41 spectral signatures for the pre- and post-tsunami images, respectively. The distribution of 60 spectral signatures used in the pre-tsunami classification image is as follows: 13 signatures representing water body, nine vegetation, three mangroves and five barren land (derived from ISODATA classification), six urban, four cloud and 20 sand (derived from training samples). The number of pixels contained in these 60 signatures amounts to more than 90% of total pixels in the image. The vast majority (more than 90%) of the pixels contained in the 60 signatures were extracted from the ISODATA unsupervised classification. For the post-tsunami analysis, the number of pixels contained in these 41 signatures amounts to more than 90% of the total pixels in the image. The supervised maximum likelihood algorithm was then performed using the final signature files to generate thematic maps. These spectral classes were finally recoded into major land cover classes according to the actual classes they represent gained from the reference data.

The pre-tsunami classified image consists of seven classes: water body, vegetation, mangrove, urban, barren land, sand and cloud (figure 6). The post-tsunami classified image had the same classes excluding the cloud (figure 6). On the pre-tsunami map, vegetation and water body were the dominant land cover classes in the study area, while for the post-tsunami map, barren land and sand were very apparent, especially in the coastal zone. There was major damage to land cover in the coastal zone area. Large tracts of vegetation and urban land cover types along the coastal area were transformed to barren land and sand after the tsunami event.

4.2 Accuracy assessment

The number of reference pixels is an important factor in determining the accuracy of the classification. In this study, 420 reference pixels were used to evaluate the accuracy of the pre-tsunami classification image. These reference pixels were selected using an equalized random sampling method. Sixty pixels were chosen for each of the seven classes in the pre-tsunami classification image. Similarly, 60 pixels for each
class were selected to access the accuracy of the post-tsunami classified image. As the class cloud was not present in the post-tsunami classification image, a total of 360 reference pixels were used in the assessment of the accuracies for the six classes in the post-tsunami classified image. The reference pixels used for the assessment of accuracy account for less than 1% of the total pixels in the image for both the pre- and post-tsunami classified images.
User’s and producer’s accuracies as well as kappa statistics for each class are reported in table 2. The overall accuracies of the pre- and post-tsunami classified images were 85.95% and 84.72%, respectively (table 2). The overall kappa statistics of the pre- and post-tsunami classified images were 0.836 and 0.817, respectively. These kappa values (i.e. >0.8) represent strong agreement between the classification map and the ground reference information (Jensen 2005).

Classes with both high producer’s and high user’s accuracies indicate a high level of classification reliability. As can be seen from the table 2, water was the best classified in both assessment categories for both the pre- and post-tsunami classified images. The accuracies for vegetation, mangrove and barren land ranged from 83% to 88% and from 80% to 90% for the pre- and post-tsunami classified images, respectively. Relatively lower levels of accuracy were obtained for sand and urban classes in both assessment categories for both the pre- and post-tsunami classified images.

Accuracies of class changes are presented in table 3. These accuracies were computed using the user’s accuracies for each class on the pre- and post-tsunami classified images.

### 4.3 Image separation and the GIS proximity model

Image separation and the proximity model helped us to visualize the characteristics of the study area. Unlike traditional change detection interpretation, the process of image separation helped in the provision of useful information to separate each

<table>
<thead>
<tr>
<th>Water</th>
<th>Vegetation</th>
<th>Mangrove</th>
<th>Urban</th>
<th>Barren land</th>
<th>Sand</th>
<th>Cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>86.24</td>
<td>75.30</td>
<td>79.30</td>
<td>68.71</td>
<td>81.09</td>
<td>70.32</td>
</tr>
<tr>
<td>Vegetation</td>
<td>80.65</td>
<td>70.41</td>
<td>74.16</td>
<td>64.25</td>
<td>75.83</td>
<td>65.76</td>
</tr>
<tr>
<td>Mangrove</td>
<td>79.81</td>
<td>69.68</td>
<td>73.39</td>
<td>63.58</td>
<td>75.04</td>
<td>65.07</td>
</tr>
<tr>
<td>Urban</td>
<td>72.44</td>
<td>63.24</td>
<td>66.61</td>
<td>57.71</td>
<td>68.10</td>
<td>59.06</td>
</tr>
<tr>
<td>Barren land</td>
<td>80.06</td>
<td>69.90</td>
<td>73.61</td>
<td>63.78</td>
<td>75.27</td>
<td>65.28</td>
</tr>
<tr>
<td>Sand</td>
<td>78.24</td>
<td>68.31</td>
<td>71.94</td>
<td>62.33</td>
<td>73.56</td>
<td>63.79</td>
</tr>
<tr>
<td>Cloud</td>
<td>95.16</td>
<td>83.08</td>
<td>87.50</td>
<td>75.81</td>
<td>89.47</td>
<td>77.59</td>
</tr>
</tbody>
</table>

### 4.4 Using GIS for post-tsunami analysis

The GIS proximity model was applied to the post-tsunami classified images to identify areas affected by the tsunami. The results were categorized into six classes: water, vegetation, mangrove, urban, barren land, and sand. The classification accuracies for each class were as follows: water (86.24%), vegetation (80.65%), mangrove (79.81%), urban (72.44%), barren land (80.06%), and sand (78.24%). The overall classification accuracy for the post-tsunami images was 84.72%, with a kappa statistic of 0.817. These results indicate a high level of agreement between the classification map and the ground reference information.
subregion into a homogeneous area before inputting classified images for change detection analysis. Table 4 summarizes the geographic characteristics of each subregion derived from image separation and the GIS proximity model.

4.4 Change detection

For change detection analysis, we considered newly formed sand and barren land areas to represent areas after the tsunami event. From image separation and the GIS proximity model, we obtained change detection matrix results for each region and six buffer distances. Tables 5 and 6 provide examples of change detection results for two buffer distances. Table 5 shows that there was very low mangrove coverage after the tsunami event in all regions, which consistently had similar spatial patterns and experienced similar severity of damage. There was a notable decrease in mangrove vegetation (ranging from 14 to 34 ha) and a significant increase in barren and sand land classes (ranging from 127 to 436 ha) in all of the four regions following the tsunami event. Urban infrastructures located along the coastline were completely destroyed and replaced by barren land and sand classes. Obviously, geographic areas that were in close proximity to the coastline experienced the most impact from the 2004 tsunami.

Additional analyses of geographic areas within 500 m of the coastline revealed some interesting results. For example, the North region had a major change from vegetation to barren land of 319 ha (5112 pixels) out of 1837 ha of the total land area in this subregion. Only about 3 ha represented mangrove after the tsunami event. The Mid region had a change from vegetation to barren land of 335 ha out of 654 ha of total land area in this subregion (i.e. a decrease of 51.17%). The Upper-South region had over 90% of urban area destroyed (564 pixels, 35 ha) out of 37 ha of the total land area in this subregion. The Lower-South had over half of its vegetation reduced to barren land and sand with an estimated 110 ha (1767 pixels) out of the total of 144 ha of vegetation.

Although the severity of the damage in the third buffer ring (1000–1500 m) was consistent with that observed in the first buffer ring, it was significantly lower for the Upper-South region (table 6). The appearance of mangroves in the Upper-South region within this buffer distance shows the benefit of mangrove forests in terms of coastal protection. Only 0.6% of total mangrove was lost to barren land and sand. Vegetation in the Upper-South region was only about 12% destroyed, which is about 11 ha out of 90 ha. Without taking the mangrove forests into account, the North, Mid and Lower-South regions still had over 50% of other vegetation types and urban areas before the tsunami that were replaced by barren land and sand (Sirikulchayanon 2006). Overall, there was a notable decrease in mangrove vegetation (from 12 to 47 ha) and a significant increase in barren and sand land classes (from 5 to 327 ha) in all of the four regions following the tsunami event.

4.5 Impact analysis of tsunami on mangrove

The damage was analysed using equation (1). There was major damage to land cover, representing an average of 26.87% change, in geographic locations with low mangrove coverage and in areas in close proximity to the coastline in all four subregions, whereas less damage was apparent in locations with high mangrove coverage, on the whole representing an average of only 2.77% change.

The percentages of mangrove and tsunami damage within different regions and their surrounding buffer rings are shown in table 7. Geographically, the
<table>
<thead>
<tr>
<th>Area</th>
<th>Image characteristics</th>
<th>Pre-tsunami</th>
<th>Post-tsunami</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>Large island off the mainland 1–3 km (width) of sand beach Densely areas of mangroves behind the beach along the coastline Somewhat urban environment</td>
<td>Dense mangrove vegetation Sizeable built-up environment</td>
<td>Less mangrove vegetation Increase in barren land and sand areas along the coastline on the island</td>
</tr>
<tr>
<td>Mid</td>
<td>A long straight coastline open to the ocean Heavily built-up environment of popular hotels, resorts and infrastructures Less mangrove or other types of natural barriers</td>
<td>Mixed type of land cover classes such as vegetation, barren land, urban areas and sand beaches along the rim of the coastline Fewer or no mangroves</td>
<td>Complete change in land cover types along the coastline Significant damage is apparent Increase in barren and sand areas along the coastline with more visible sand</td>
</tr>
<tr>
<td>Upper-South</td>
<td>A relatively narrow beach Dense areas of mangrove coverage in the form of a thin line extending inland next to the beach and along the total length of the coast</td>
<td>Mixed land cover types along the coastal zone Sizeable mangrove patches in the shape of a thin line next to the beach</td>
<td>The long beach and a group of vegetation located in front of the mangrove patches Increase in barren land</td>
</tr>
<tr>
<td>Lower-South</td>
<td>A relatively narrow beach, almost no river mouth Fewer or no mangroves along the coastline Less built-up environment and few infrastructures</td>
<td>Mixed land cover types and sizeable area covered by vegetation A long beach, similar to the Upper-South region Fewer or no mangrove forests</td>
<td>Areas beyond mangrove vegetation remain mostly unchanged Most coastal zone areas replaced with sand while barren land areas have expanded Decrease in vegetation</td>
</tr>
</tbody>
</table>
Upper-South and Lower-South regions are almost identical, but because of low mangrove coverage, the Lower-South region experienced serious and extensive damage after the tsunami event. We also observed that in densely populated mangrove regions, especially in the North and Upper-South regions, the areas consistently had less damage, whereas in the Mid and Lower-South regions with low mangrove coverage, there was consistently high damage throughout most of the areas. From these data, we could also conclude that mangrove areas are less impacted by the tsunami than other types.
of land cover. It was evident that other vegetations were completely destroyed, but
the mangrove vegetation survived the tsunami waves. For instance, the Upper-
South region appeared to have high percentages (44–46%) of mangrove in 500–
1500 m rings, where the percentage of damage was significantly lower than other
regions without mangroves. The greater percentage of mangroves in the North
region within 1500–3000 m also yielded a similar result of less impact. The data
clearly demonstrate that mangrove forests could act as a wave absorber and areas
behind the mangrove forests also benefitted from this protection.

<table>
<thead>
<tr>
<th>Post-tsunami</th>
<th>Water</th>
<th>Vegetation</th>
<th>Mangrove</th>
<th>Urban</th>
<th>Barren land</th>
<th>Sand</th>
<th>Cloud</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td><strong>North region</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
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<td>163</td>
<td>97</td>
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<td>113</td>
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<td>0</td>
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<td>325</td>
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<td>0</td>
<td>1943</td>
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<td>Mangrove</td>
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<td>392</td>
<td>0</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>483</td>
</tr>
<tr>
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<td>85</td>
<td>267</td>
<td>315</td>
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<td>718</td>
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<td>101</td>
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<td>25</td>
<td>1103</td>
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<td>24</td>
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<td>43</td>
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<td>81</td>
<td>237</td>
<td>1</td>
<td>15</td>
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<td>0</td>
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<td>501</td>
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<td>Sand</td>
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<td>Total</td>
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<td>9284</td>
<td>537</td>
<td>1249</td>
<td>13857</td>
<td>3031</td>
<td>272</td>
<td>29184</td>
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<td>3</td>
<td>3</td>
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<td>0</td>
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<tr>
<td>Barren land</td>
<td>19</td>
<td>172</td>
<td>25</td>
<td>20</td>
<td>280</td>
<td>120</td>
<td>3</td>
<td>639</td>
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<tr>
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<td>2</td>
<td>22</td>
<td>4</td>
<td>17</td>
<td>58</td>
<td>162</td>
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<td>265</td>
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<tr>
<td>Total</td>
<td>3105</td>
<td>1433</td>
<td>4775</td>
<td>45</td>
<td>507</td>
<td>322</td>
<td>83</td>
<td>10270</td>
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<tr>
<td><strong>Lower-South region</strong></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Water body</td>
<td>131</td>
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<td>0</td>
<td>2</td>
<td>36</td>
<td>5</td>
<td>0</td>
<td>273</td>
</tr>
<tr>
<td>Vegetation</td>
<td>15</td>
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<td>160</td>
<td>12</td>
<td>639</td>
<td>22</td>
<td>0</td>
<td>1915</td>
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<tr>
<td>Mangrove</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Urban</td>
<td>0</td>
<td>10</td>
<td>1</td>
<td>33</td>
<td>55</td>
<td>39</td>
<td>0</td>
<td>138</td>
</tr>
<tr>
<td>Barren land</td>
<td>52</td>
<td>1312</td>
<td>91</td>
<td>267</td>
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<td>532</td>
<td>1</td>
<td>5348</td>
</tr>
<tr>
<td>Sand</td>
<td>6</td>
<td>159</td>
<td>10</td>
<td>411</td>
<td>1359</td>
<td>590</td>
<td>1</td>
<td>2536</td>
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<tr>
<td>Total</td>
<td>206</td>
<td>2648</td>
<td>263</td>
<td>725</td>
<td>5182</td>
<td>1188</td>
<td>2</td>
<td>10214</td>
</tr>
</tbody>
</table>

Each pixel is equivalent to 25 m × 25 m.
A notable decrease was observed in mangrove vegetation (ranging from 12 to 47 ha) and a
significant increase in barren and sand land classes (ranging from 5 to 327 ha) in all of the four
regions following the tsunami event. The Mid region experienced the most change in the
barren and sand land classes (most damage) and a significant loss of mangrove was found in
the North Region, but less damage was observed in the Upper-South region.

Table 6. Cross-tabulation results (number of pixels) for buffer distance 1000–1500 m from the
coastline.
4.6 \( \chi^2 \) analysis of impacted areas

Table 8 shows a \( \chi^2 \) distribution of the four regions and their surrounding buffer distances. The North and Upper South regions have statistically significant distributions (\( \chi^2 \) test, df=5, \( p \leq 0.001 \)). Table 9 shows a \( \chi^2 \) distribution of the comparisons of geographic proximity of areas within 500 m from the coastline, with other areas located further away. Similarly, in table 9, the North and Upper South regions consistently have statistically significant results (\( \chi^2 \) test, df=9, \( p \leq 0.001 \)). The other two regions in both analyses were not statistically significant. In comparing the presence of mangrove forests and barren and sand land cover categories before and after the tsunami in the entire study region, we observed positive linear relationships, suggesting change in mangrove to loss of mangrove and a gain in barren and sand land cover experienced resulting in a devastating impact from the 2004 tsunami events. Preliminary statistical analysis confirms further that

### Table 7. Percentage of damage and mangrove area in each subregion according to buffer distance.

<table>
<thead>
<tr>
<th>Region</th>
<th>Buffer distance (m)</th>
<th>0–500</th>
<th>500–1000</th>
<th>1000–1500</th>
<th>1500–2000</th>
<th>2000–2500</th>
<th>2500–3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>Damage</td>
<td>25.32</td>
<td>22.91</td>
<td>19.24</td>
<td>13.10</td>
<td>14.24</td>
<td>11.08</td>
</tr>
<tr>
<td></td>
<td>Mangrove</td>
<td>1.03</td>
<td>1.06</td>
<td>4.27</td>
<td>12.30</td>
<td>24.76</td>
<td>34.32</td>
</tr>
<tr>
<td>Mid</td>
<td>Damage</td>
<td>29.93</td>
<td>23.22</td>
<td>22.54</td>
<td>18.19</td>
<td>16.63</td>
<td>17.98</td>
</tr>
<tr>
<td></td>
<td>Mangrove</td>
<td>1.83</td>
<td>1.36</td>
<td>1.84</td>
<td>5.85</td>
<td>3.73</td>
<td>3.39</td>
</tr>
<tr>
<td>Upper-South</td>
<td>Damage</td>
<td>25.33</td>
<td>9.07</td>
<td>2.77</td>
<td>2.81</td>
<td>6.19</td>
<td>5.46</td>
</tr>
<tr>
<td></td>
<td>Mangrove</td>
<td>3.21</td>
<td>44.29</td>
<td>46.49</td>
<td>12.92</td>
<td>6.93</td>
<td>33.94</td>
</tr>
<tr>
<td>Lower-South</td>
<td>Damage</td>
<td>26.90</td>
<td>30.44</td>
<td>22.62</td>
<td>20.02</td>
<td>21.15</td>
<td>17.78</td>
</tr>
<tr>
<td></td>
<td>Mangrove</td>
<td>2.22</td>
<td>3.39</td>
<td>2.57</td>
<td>0.95</td>
<td>0.99</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Damage represents the percentage of newly formed sand and barren land areas assumed to be the result of tsunami impact. Mangrove represents the actual percentage of mangrove coverage in the area.

It is apparent that where there is a high density of mangrove coverage, for example in the North and Upper-South regions, we consistently observed less damage, and where there is low density of mangrove coverage, for example in the Mid and Lower-South regions, we consistently observed high damage.

### Table 8. \( \chi^2 \) distribution of the four regions and their surrounding buffer distances.

<table>
<thead>
<tr>
<th>Region</th>
<th>( \chi^2 ) statistics</th>
<th>( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>63.78</td>
<td>( \leq 0.001^* )</td>
</tr>
<tr>
<td>Mid</td>
<td>6.98</td>
<td>( \leq 1.000 )</td>
</tr>
<tr>
<td>Upper-South</td>
<td>78.12</td>
<td>( \leq 0.001^* )</td>
</tr>
<tr>
<td>Lower-South</td>
<td>1.57</td>
<td>( \leq 1.000 )</td>
</tr>
</tbody>
</table>

A bivariate table (2 × 6) was created for each region to measure less and more impacted areas based on mangrove data and six buffer distances (yielding 5 degrees of freedom). Statistical significance level is \( p \leq 0.05 \).

*These distributions are statistically significant.
areas with low and high mangrove coverage consistently had similar spatial patterns of major and less damage, correspondingly.

5. Discussion and conclusion

Unlike the traditional approach of considering an area as a whole, our approach provides more specific information from the change detection by dividing the study area into smaller buffer zones. The combination of techniques effectively allowed us to establish strong statistical relationships between the different distances from the coastline and the severity of the damage caused by the tsunami waves. The findings show that an optimum distance between 1000 and 1500 m of mangrove buffer would be favourable and most effective for reducing the damage by potential tsunami waves.

The obvious effect of the tsunami was notable within a distance of 3 km from the coastline. The impact was highest at the beach and decreased as the distance increased, as demonstrated by the GIS proximity model. In every region, major damage occurred on vegetation and urban land cover types. The areas near the beach also showed comparable levels of damage in all regions with an average of 26.87%. The Mid and Lower-South regions showed an estimated impact level of 16–30% through the entire regions with a relatively small number of mangroves of less than 5%, while in the North and Upper-South regions, where the spatial distribution of mangrove forests was significant, some buffer distances showed an estimated impact level ranging from 2% to 25%. The fourth buffer ring (1500–2000 m) provided distinctive results that further illustrated the benefits of the mangrove’s potential as a tsunami impact reducer. Within this buffer distance, the North and Upper-South regions had 12.30% and 12.92% of mangrove vegetation, respectively, and other buffers also had a sizeable number of mangrove vegetation, which accounted for the lowest percentages of impact (13.10% and 2.81%, respectively) in comparison to the Mid (18.19%) and Lower-South (20.02%) regions.

Bivariate statistical analyses also confirmed that there were strong spatial relationships between the impacts of tsunamis on geographic regions with mangrove vegetation coverage and those without this type of vegetation. The analyses suggest that there was less or no damage caused by the tsunami in areas with mangrove vegetation coverage, and locations without this vegetation experienced a high impact from the 2004 tsunami.

In this study, we have established that mangrove vegetation resisted the powerful force of the tsunami much better than regular vegetation. The stronger root system...
of the mangroves may be the main factor. Our findings have provided additional empirical data that is consistent with previous studies (Mazda et al. 2002, Kathiresan and Rajendran 2005). Immediately following the December 2004 tsunami, Kathiresan and Rajendran (2005) reported no loss of lives or few losses in the coastal area of Tamil Nadu State of India, which is situated behind dense mangroves within a distance ranging from 1 to 2.5 km away from the coastline. In an earlier study, Mazda et al. (2002) also demonstrated the usefulness of mangroves in shoreline protection from waves in Vietnam.

This study experienced a number of limitations. First, this was the only historical tsunami event ever recorded in the region in past decades; therefore, only a few previous studies existed and some of the thresholds of the GIS proximity model could not readily be established. Second, several variables, such as slopes and the distance from the tsunami epicentre, were assumed to have no significant effect throughout the period of study. We believe that this technique, together with the combination of multiple sources of data, was valuable in facilitating the analysis of the impact of the 2004 tsunami; however, there is still a need to evaluate these findings further and possibly also to conduct field work to improve the interpretations of the results. Nevertheless, our results established some of the benefits of mangrove forests in terms of being a natural barrier to coastal communities against such a disaster.

Many opportunities exist to expand this study in the future and additional analysis will be forthcoming. Similar studies could be conducted in other affected countries to obtain additional information. These findings provide a basis for policy formulation regarding mangrove forest rehabilitation and management along the coastline of Thailand. An appropriate mangrove replantation site should be considered. Specifically, future studies could identify which species of mangroves would be more effective and suitable to help to reduce the power of future tsunamis.

Acknowledgements
Special thanks for constructive comments and recommendations from the anonymous reviewers on an earlier draft of this paper. We also thank the Faculty and Administrative Staff of the Department of Geography and Environmental Resources, Southern Illinois University, for their encouragement and support.

References
BLASCO, F., 1975, The Mangroves of India, Institut Francais de Pondichéry, Pondicherry. Travail de la Section Scientifique et Technique (Pondicherry: All India Press); 14, pp. 1–175.
CHAPMAN, V.J., 1976, Mangrove Vegetation (Vadaz: Cramer).


