WALAILAK JOURNAL
http://wjst.wu.ac.th Engineering and Physical Sciences

Assessing Coastal Land Cover Changes after the 2004 Tsunami Using Remote Sensing and GIS Approaches

Pasu KONGAPAI, Penjai SOMPONGCHAIYAKUL and Somrudee JITPRAPHAI*

Department of Marine Science, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand

(*Corresponding author's e-mail: somdeem@gmail.com)

Received: 3 April 2015, Revised: 16 October 2015, Accepted: 19 November 2015

Abstract

Land cover change analysis can be applied in order to understand the impacts of natural disasters. These results are critical for addressing future planning needs. This study assessed long-term land cover changes at Khao Lak, Thailand, which were severely affected by the 2004 tsunami, by applying Geographic Information System analyses, including change detection using remotely sensed imagery. Results revealed that urban areas were highly impacted by the tsunami, decreasing considerably moving landwards, with an 85 % change recorded at 225 m from shoreline, whereas vegetated areas showed relatively little change 1 km from shore. The period after the tsunami (2005 - 2008) showed considerable change: water bodies were reduced by 42 %, mainly turned into barren land, at 26.2 %, with a lesser amount changed into urban areas, 0.1 %, at 75 m from shore. Five years later (2008 - 2013), barren land areas had gradually increased to 44 %, while water bodies declined by 53 % at 75 m inland. Additionally, urban areas had increased up to 1 km landwards. Land cover changes varied between land cover types and their distances from shoreline or coastal proximity. Findings should prove valuable for understanding coastal hazard impacts in relation to land cover types, and also guide planning policy, such as setting a minimum distance from the shore for urban development.

Keywords: Tsunami, land cover, change detection, setback line*,* remote sensing

Introduction

The 2004 Indian Ocean tsunami earthquake created powerful waves that hit the Andaman Sea coast of southern Thailand. Six coastal provinces experienced severe damage, including Phang Nga, where some 4,224 lives were lost and 7,003 ha of land area devastated [1]. Phang Nga's coastal area of Khao Lak was especially badly impacted. Khao Lak had increasingly developed land for coastal tourism since 1988. Rapid development was reflected in more hotels, resorts, restaurants and houses along the shoreline, including hotel capacity increasing from 100 rooms in 1996 to 5,315 rooms by December 2004 [2]. The area is a popular tourist hotspot, with villages located along the coast. The 2004 tsunami greatly damaged the area, with floods penetrating 2 km inland, resulting in some of the highest numbers of casualties and missing people, both tourists and local residents, in Thailand [3]. Buildings and infrastructure were destroyed along the coast [4], and coastal vegetation uprooted and washed away [5].

The impact of the tsunami was influenced by several factors, such as coastal land elevation, slope, bathymetry, topography, built environment, coastal vegetation, and the presence of natural vegetated areas [6-9]. Additionally, land topography influenced the degree of damage, with the latter reducing on moving inland from the shore [4]. Regarding the assessment of natural environment vulnerability after the 2004 tsunami, previous studies have assessed damage in Thailand through land use change analyses [10-12]. Impacts on natural resources were assessed by a variety of studies: on the beaches and Bang Niang tidal channels of Khao Lak [13]; damage assessment of coral reefs [14]; coastal forest sensitivity in the coastal zone of Phang Nga province; mangrove forest degradation [8,15,16]; and evaluation of the role of mangrove forests for mitigating tsunami impacts [17].

Information on land use and land cover change is critical for future planning and mitigation of potential future tsunami impacts. This study aims to understand the impacts of the tsunami on different land cover types, so as to inform future preparedness planning. Given that the coastal zone is an area with growing human settlements and socio-economic activities [18-20] it is also at greater risk to environmental hazards. Furthermore, determining the appropriate distance from the shoreline for development is important in lessening the impacts of coastal hazards such as coastal erosion, sea level rise, storm surge, and tsunamis.

The study investigated hazard impacts by relating land cover types with coastal proximity, the approach combining change detection of remote sensing imagery (IKONOS and THEOS) and creation of multiple buffer distances reflecting coastal proximity to analyse patterns of land cover changes from 2003 to 2013. Specifically, the study examined changing land cover characteristics, including: 1) tsunami impacts to land cover types; 2) identification of buffer distances showing highest exposure; and 3) recovery patterns of land cover types. The analysis of land cover changes in coastal proximity during 2003 to 2013 using the technologies of remote sensing and GIS, especially at Khao Lak, has not previously been reported.

Materials and methods

Study area

The study area is located at Khao Lak village, in the Takua Pa District, and partly in the Thai Mueang District, of Phang Nga Province, in southern Thailand. The area covers 15.72 km^2 along a coastal strip bounded between latitude 98º 13' 10" to 98º 15' 37" and longitude 8º 38' 4" to 8º 44' 26" (**Figure 1**). Khao Lak is well-known for its coastal tourism, characterized by surrounding resorts, hotels positioned close to the shore, and other distributed resorts in hilly areas. The coastal terrain is a relatively flat area along the coastline, stretching almost 2 km inland. Nearshore areas are gently sloping, with several tidal inlets and large patches of tropical vegetation, such as beach forest, mangroves, Casuarina forest, and coconut plantations. After the 2004 tsunami, Khao Lak was the worst hit area in Thailand, experiencing the highest number of casualties and missing people, and with 80 % capacity of its hotels and resorts lost [21].

Buffer zones were established by the Thai Building Control Act B.E. 2554 (A.D. 2011) under Thailand's Ministry of the Interior. Regulations set out conditions for construction or modification or change of buildings, except for some building types in Amphoe Khura Buri, Amphoe Takua Pa, Amphoe Thai Mueang, Amphoe Mueang Phang Nga, Amphoe Thap Put, Amphoe Takua Thung, and Ko Yao of Phang Nga Province, Thailand.

The regulations defined the width of the buffer zones from the mean high-water mark as: 1^{st} Zone (75 m) 0 - 75 m; 2^{nd} Zone (150 m) 75 - 225 m; and 3^{rd} Zone (300 m) 225 - 525 m. Although it is not defined by Thai law, the additional 4^{th} buffer zone, 1 km landwards (475 m) 525 - 1,000 m, is suggested and used in this study. This is due to a number of reasons: 1) the extended area was highly populated and damaged by the 2004 tsunami, and 2) the damaged vegetated areas (beach forest and mangrove forest) were found further than 1,000 m landward.

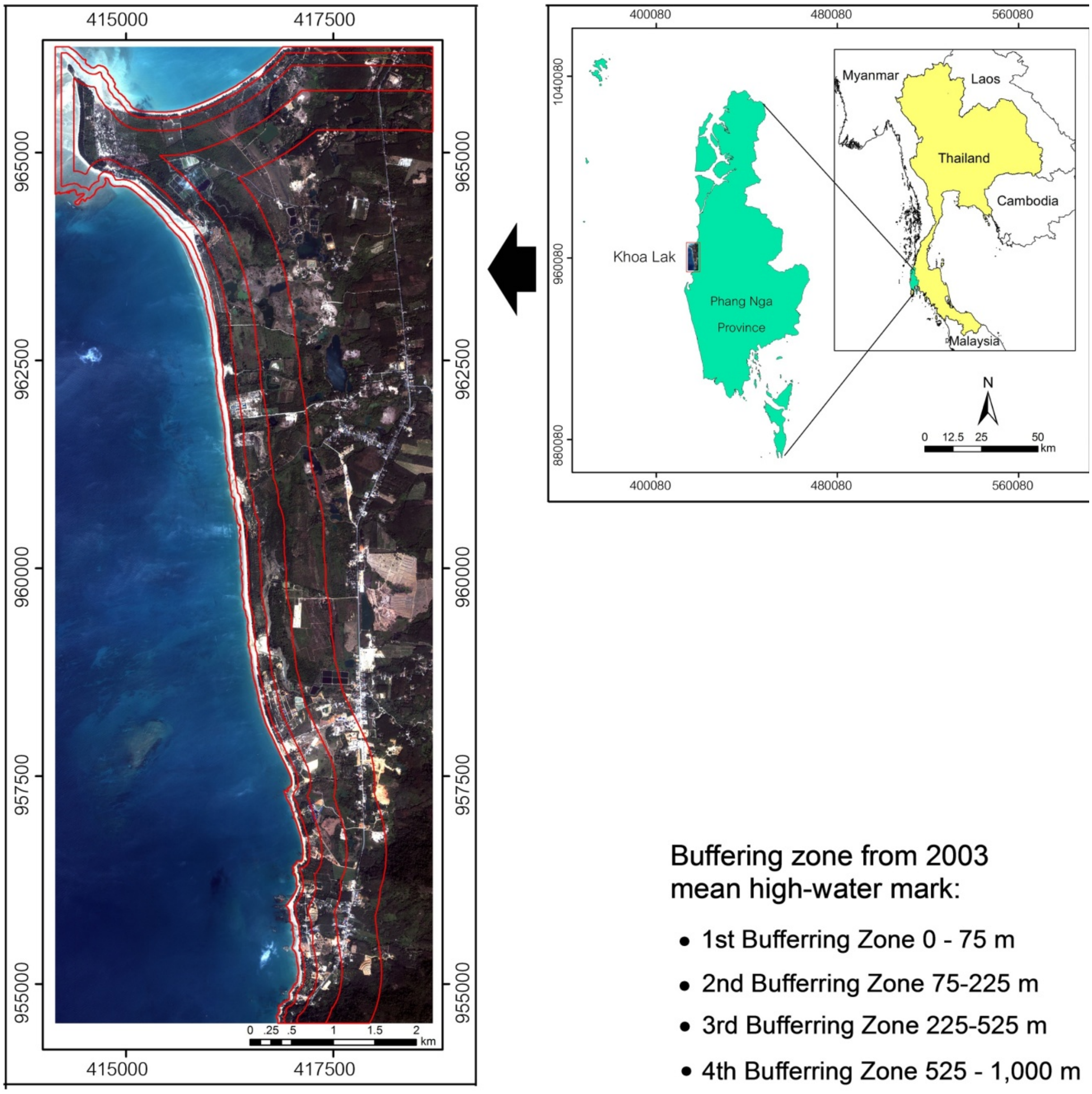

Figure 1 The study area: Khao Lak, Phang Nga Province, southern Thailand. The area was severely damaged by the 2004 Tsunami.

Datasets used

A series of multi-date IKONOS images were acquired from the Centre of Remote Sensing and Processing (CRISP) in Singapore, and Spatial Dimension Solutions (SDS) in Bangkok (Thailand). The THEOS imagery was acquired from the image archives of Geo-Informatics and Space Technology Development Agency (Public Organization) (GISTDA) in Bangkok. Multi-spectral bands enabled land cover classification, whereas the higher resolution pan-sharpened data were used for validation purposes (**Table 1**). Images of different resolutions were used, due to the limited availability of appropriate cloud-free images of IKONOS scenes for the date in 2012. Therefore, the THEOS image in 2013 that was available and acquired from GISTDA has the same spectral range as the IKONOS image. THEOS's panchromatic band has a wide spectral range, from visible to near-infrared (NIR). In this case, the THEOS image can improve the lower resolution image by applying pan-sharpening using the high-resolution panchromatic image.

Table 1 Satellite images used in this study.

Satellite Platform (No. of scenes)	Spectral Range (μm)		Spatial Resolution (m)	Acquisition Date
IKONOS (3 scenes)	Pan	0.45 - 0.90	1	13 January 2003
	Blue	0.45 - 0.52	4	15 January 2005
	Green	0.52 - 0.60	4	20 January 2008
	Red	0.63 - 0.69	4	
	NIR	0.76 - 0.90	4	
THEOS (1 scene)	Pan	0.45 - 0.90	2	4 February 2013
	Blue	0.45 - 0.52	15	
	Green	0.53 - 0.60	15	
	NIR	0.77 - 0.90	15	

Note: IKONOS images were acquired from the Centre of Remote Sensing and Processing (CRISP) in Singapore, and Spatial Dimension Solutions (SDS) in Bangkok (Thailand). THEOS image was acquired from the Geo-Informatics and Space Technology Development Agency (Public Organization) (GISTDA) in Bangkok.

Image analysis methods

The approach adopted included: 1) pre-processing; 2) image pan-sharpening; 3) image classification; 4) accuracy assessment; 5) creation of buffer zones; and 6) change detection. These 6 steps (**Figure 2**) were applied for assessing land cover changes after the 2004 tsunami and for determining impacts in relation to coastal proximity.

Pre-processing

Pre-processing of satellite images was necessary before applying classification and change detection techniques. The pre-tsunami scene of 2003, and pan-sharpened multispectral (RGB) 2 m, were first registered by using a set of 53 ground control points (GCPs), selected from building corners, crossroads, and noticeable landmark objects. The post-tsunami scenes of 2005, 2008, and THOS 2013 were warped to the base image. The co-registration root-mean-square error (RMSE) of the images were achieved between 0.45 - 0.50. The RMSE was well under less than one pixel in order that the images were suitable to allow performance of the orthorectification [22].

Image pan-sharpening

The purpose of pan-sharpening is for 3 reasons: to increase the spatial resolution of THEOS multispectral data for classification; to select training areas for classification accuracy assessment; and to visually validate classifications from 2003, 2005, and 2008 imagery. The technique applied panchromatic imagery (high spatial 2 m resolution) to multispectral images (low spatial 15 m resolution) by applying the Gram-Schmidt (GS) spectral sharpening approach [23,24]. Before image sharpening, multispectral images were co-registered to the corresponding panchromatic images and resampled to the same pixel size as the panchromatic images. Images were resampled using the nearest-neighbour resampling technique, as this maintained original pixel values. Importantly, an efficient pan-sharpening method should not only increase the spatial resolution of the multispectral data, but should maintain the spectral integrity of the multispectral data as well [23]. The resulting pan-sharpened images were used to visually select training areas and to identify appropriate test sites for accuracy assessment.

Image classification

Before classification, IKONOS and THEOS images were used to mask out clouds and ocean and used for classification. A maximum likelihood supervised classification used signatures from training sites, as presented in **Table 2**. Five classification images, from 2003, 2005, 2008, and 2013, display vegetation, barren land, urban areas, water bodies, and aquaculture classes. The classification approach involved three steps, or levels of analysis. The first level classified water and non-water areas in order to eliminate errors arising from mixed pixels. The second level created vegetation and non-vegetation classes. The third level identified barren land and urban areas from non-vegetated classes. The final step recoded some water bodies into aquaculture, given that the shape and pattern of aquaculture areas were different from water bodies.

Table 2 Classification definitions.

Land cover types	Classification definitions
Vegetation	Tropical rain forest, mangrove forest, beach forest, mixed forest lands, scrub, and agricultural areas
Barren land	Land areas of exposed soil surface, such as beach sand dunes and areas with sparse plant cover
Urban areas	Hotels, resorts, residential, commercial and services, transportation including roads
Water bodies	River, permanent open water, lakes, ponds, reservoirs and open water, channels and waterways
Aquaculture	Farming of aquatic organisms, including; fish, shrimp, molluscs, crustaceans and aquatic plants

Accuracy assessment

Accuracy assessment is an important part of validating image classification and change detection [25]. Validation points were from pan-sharpened imagery for the 2003, 2005, and 2008 classification maps. Ground truth data from a field trip, conducted from July - August 2012, was used for assessing classification accuracy for 2013.

Created buffering zones

Variable buffer zones (**Figure 1**) were created in ArcGIS. The coastline for the thematic maps was digitized from the high tide water mark of the pre tsunami image acquired in 2003. This was used as a reference coastline for the subsequent images of 2005, 2008 and 2013. This coastline was used to build the boundary of polygons from the coastline, and the widths of the buffer zones were defined as: 1st buffer distance 75 m with width of 0 - 75 m; 2nd buffer distance 150 m with width of 75 - 225 m; 3rd buffer distance 300 m with width of 225 - 525 m; and 4th buffer distance 475 m with width of 525 - 1,000 m. Then, the buffer zones were used to clip classified images and extract areas of interest for change detection analysis.

Change detection

Change detection is an important technique for assessing spatial-temporal changes in land cover [26]. Following classification of multi-year imagery, a multi-date change detection comparison was used to identify changes in land cover/land use, based on co-registered multi-temporal imagery from 3 different time periods (2003 - 2005, 2005 - 2008, and 2008 - 2013). To obtain measures of spatial change, a cross-tabulation was conducted for classified image pairs.

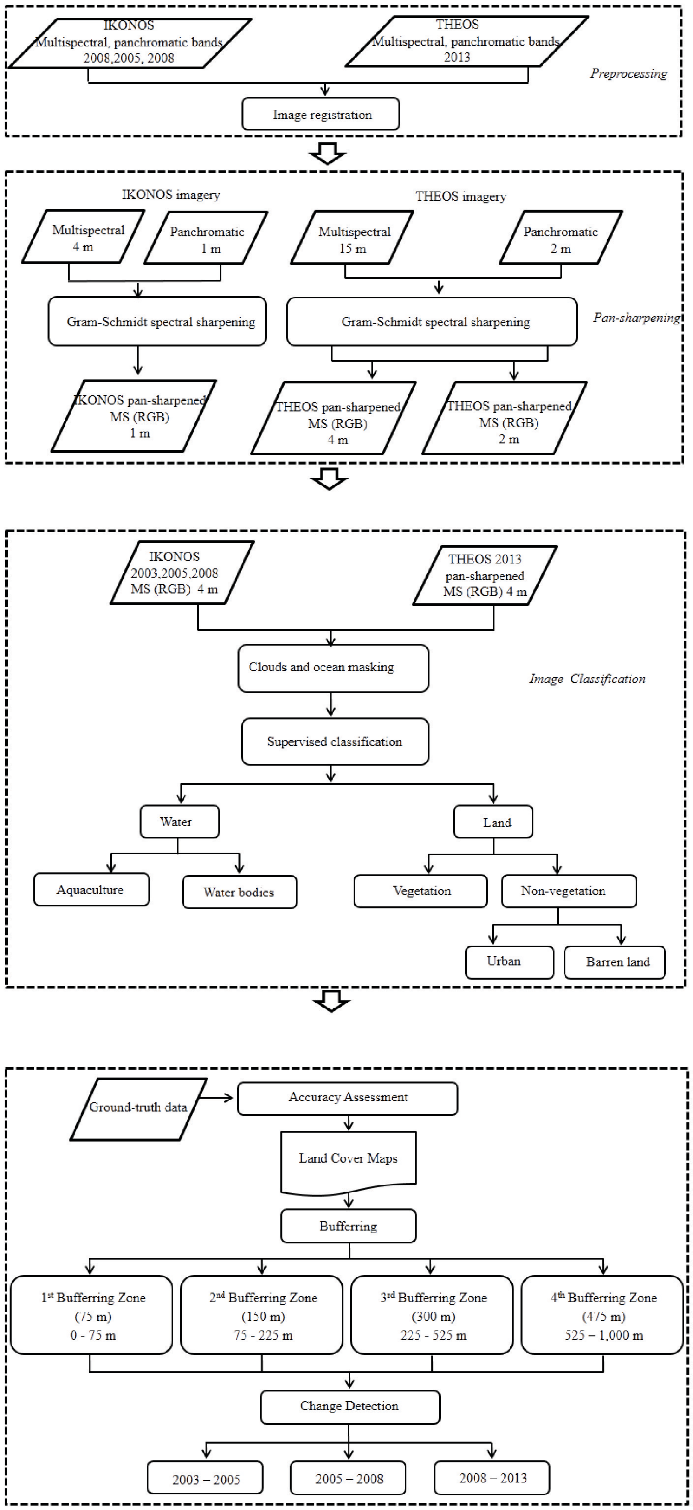

Figure 2 Flowchart of procedure for assessing land cover changes in different coastal buffer zones using remote sensing and GIS.

Results and discussion

Image classification

After registering images, clouds and ocean were masked out of all images before conducting the classification. IKONOS and THEOS images were classified for the years 2003, 2005, 2008, and 2013, and the resulting thematic layers were categorized into 5 classes: vegetation, barren land, urban areas, water bodies, and aquaculture (**Figure 3**).

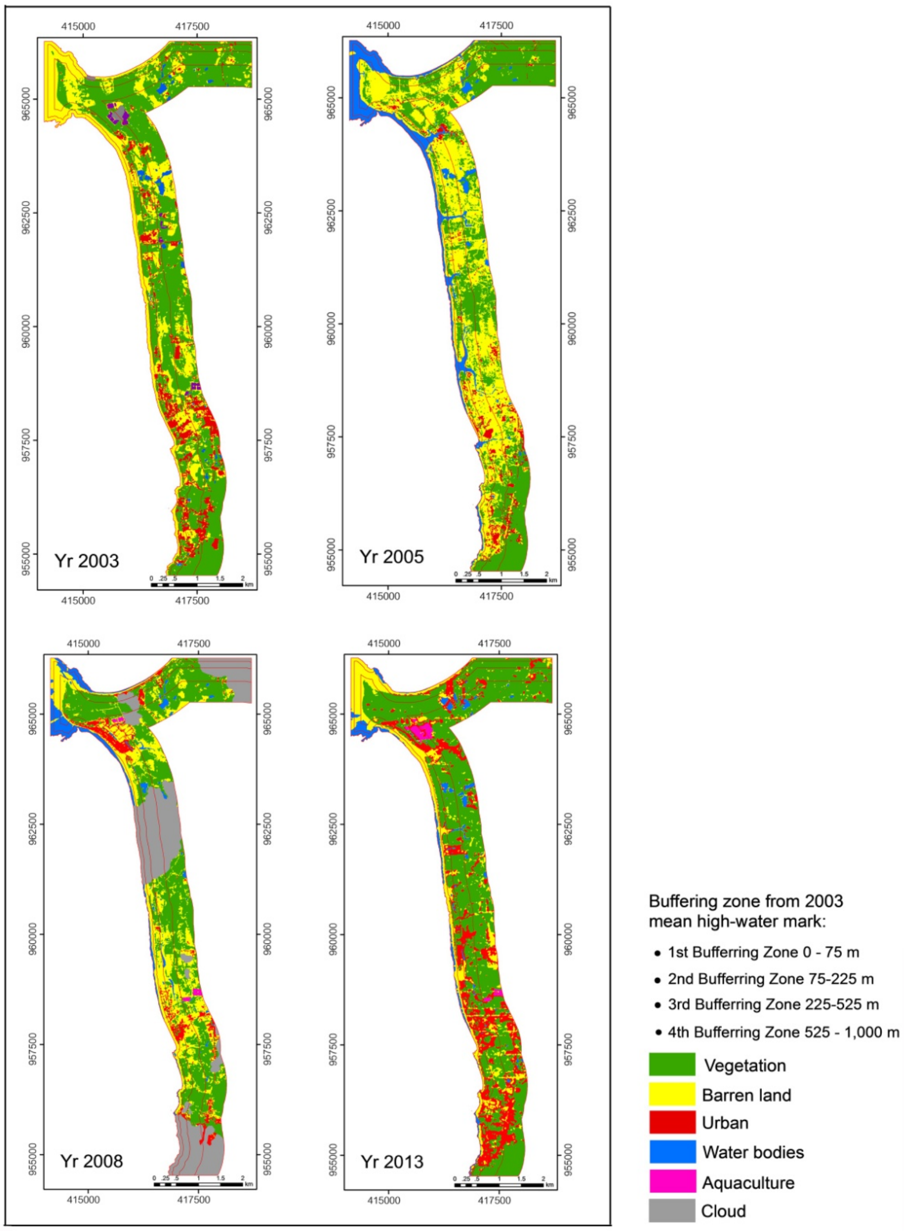

Figure 3 Thematic maps derived from classification of land cover from IKONOS (2003, 2005, and 2008) and THEOS (2013) images.

Classification results showed that the dominant land cover classes before the tsunami event in 2003 were vegetation and barren land, while the post-tsunami map of 2005, especially in the first buffer zone, showed increasing water coverage. Additionally, the area of barren land increased, resulting from building and vegetation damage since 2003 (**Figure 3**).

The IKONOS image of 2008 was obstructed by clouds, and classification was not possible for the entire area. However, a partial classification of the area was conducted to determine changes in land cover types in the period from 2005 to 2008. While the classified image was obscured by clouds in the first and second buffer zones, the dominant classification types were vegetation and barren land. In the THEOS classified image of 2013, the dominant classes were vegetation and urban areas.

Challenges were encountered in this study due to the limitations and uncertainties of using satellite images. IKONOS images in 2003 and 2008 were considerably obstructed by cloud cover, because the area is located in a humid tropical region; it is difficult to acquire cloud free imagery in this region. Future studies are recommended using additional high resolution satellite imagery, including more images acquired during the study period.

Accuracy assessment

Pan-sharpened images were used to visually select validation points for the 2003, 2005, and 2008 classification maps, verified from field trips, for accuracy assessment of classification maps for 2013. The number of reference pixels is an important factor in determining classification of accuracy. In this study, 292 reference pixels of all images were used to evaluate the accuracy of classification classes. At least 73 sample points of each image were required for the classification accuracy assessment. These numbers should permit an allowable error of 5 % of the estimated accuracy at a 95 % confidence level [27].

The overall accuracies of the classified images in 2003, 2005, 2008, and 2013 were 89.04, 91.78, 91.78, and 83.56 %, respectively (**Table 3**). The overall kappa statistics of the classified images in 2003, 2005, 2008, and 2013 were 0.82, 0.89, 0.89, and 0.73, respectively. Additionally, these kappa values > 0.8 represent strong agreement between the classification of maps and the ground truth reference points [28]. However, THEOS's kappa statistic was lower than the others because of the pan-sharpening approach. While pan-sharpening processing aims to sharpen a multispectral band with a panchromatic band, a negative consequence seen was discolouration, where urban areas tended to yellow rather than more white, and vegetation appeared bluer rather than green, which affected the classification.

Land cover maps had a reasonably high overall accuracy, though the urban area and barren land classes showed greater confusion due to similar spectral reflection. The water body class had the highest classification accuracy in all images. In addition, a high level of classification reliability is indicated by both high producer and user accuracies.

Table 3 Accuracy assessment of classified images.

	2003		2005		2008		2013	
	Producer accuracy	**User accuracy**	**Producer accuracy**	**User accuracy**	**Producer accuracy**	**User accuracy**	**Producer accuracy**	**User accuracy**
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Vegetation	95.00	95.00	96.67	90.63	100.00	96.43	92.86	97.50
Barren land	81.82	94.74	86.67	92.86	64.71	100.00	61.54	66.67
Urban areas	71.43	50.00	75.00	75.00	100.00	50.00	71.43	58.82
Water bodies	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Aquaculture	100.00	100.00	–	–	100.00	100.00	100.00	100.00
Cloud	100.00	100.00	–	–	100.00	100.00	–	–
Overall classification Accuracy	89.04		91.78		91.78		83.56	
Kappa Coefficient	0.82		0.89		0.89		0.73	

Change detection results

Confusion matrix results of change detection are presented in **Tables 4 - 6**. The results showed unchanged areas located along the diagonal of the matrix. Percentage changes are sorted by area in descending order. Changes in land cover types, from 2003 to 2005, are shown in **Table 4**.

Of the five land cover types, the greatest change was observed for the urban area class. Urban areas were significantly decreased from the shoreline to 1 km inland, especially for the 2 most seaward buffer zones, which decreased 87.6 and 83.1 %, respectively. Barren land areas for the 2 zones closest to the shoreline were converted to water bodies, at 73 and 53 %, respectively. In contrast, vegetated areas only slightly changed across all buffer zones. Overall, during this period, water bodies increased 80,940 and 5,109 % in the 2 buffer zones to 225 m inland, and decreased in the third and fourth buffers.

The most significant impact of the tsunami was notable within 225 m of the shoreline. The impact was highest near the shoreline, and decreased on moving landwards [29], as demonstrated by change detection results. In every buffer, major changes were observed in urban and barren land areas. However, vegetated areas decreased by approximately 40 % in each buffer, which reflects similar observations for coastal vegetation as reported elsewhere [18]. The extent of the damage to coastal vegetation is related to vegetation type, structure, and thickness [5,6,30].

Table 4 Confusion matrix for the land cover changes from 2003 to 2005.

2005	**2003**									
	Vegetation		**Barren Land**		**Urban**		**Water**		**Total 2005**	**Relative change**
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**2003 - 2005 (%)**
0 - 75 m										
Vegetation	18.3	64.1	2.4	2.2	0.8	14.0	0.0	11.7	21.6	-25
Barren land	9.3	32.5	26.5	24.0	3.9	70.4	0.0	21.7	39.7	-64
Urban areas	0.7	2.3	0.8	0.8	0.7	12.4	0.0	0.0	2.2	-61
Water	0.3	1.1	80.5	73.0	0.2	3.2	0.1	66.7	81.0	80,940
Total 2003	28.6	100	110.3	100	5.6	100	0.1	100		
75 - 225 m										
Vegetation	83.5	60.5	6.7	6.7	5.0	14.7	0.3	23.9	95.5	-31
Barren land	48.5	35.1	38.2	38.0	21.7	63.8	0.2	21.9	108.6	8
Urban areas	3.9	2.8	2.5	2.5	5.7	16.9	0.2	14	12.2	-64
Water	2.3	1.6	53	52.8	1.6	4.6	0.5	40.3	57.3	5,109
Total 2003	138.1	100	100.4	100	34.0	100	1.1	100		
225 - 525 m										
Vegetation	172.4	58.6	18.1	12.2	5.0	10.2	0.2	3.6	195.8	-33
Barren land	110.9	37.7	108.9	73.6	32.3	65.4	0.3	5.6	252.4	71
Urban areas	6.9	2.4	7.1	4.8	11.4	23.1	0.0	0.2	25.5	-48
Water	4.1	1.4	13.9	9.4	0.6	1.3	4.8	90.6	23.4	342
Total 2003	294.3	100	148	100	49.3	100	5.3	100		
525 - 1000 m										
Vegetation	293.7	68.4	30.8	23.9	10.2	16.5	1.3	7.4	336	-22
Barren land	118.3	27.6	89.6	69.6	37	59.8	1.1	6.2	246	91
Urban areas	14.4	3.4	6.3	4.9	14.6	23.6	0.8	4.9	36.1	-42
Water	2.9	0.7	2.1	1.6	0.1	0.2	14.1	81.5	19.2	11
Total 2003	429.2	100	128.8	100	61.8	100	17.3	100		

Table 5 Confusion matrix for the land cover changes from 2005 to 2008.

2008	**2005**									
	Vegetation		**Barren Land**		**Urban**		**Water**		**Total 2008**	**Relative change**
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**2005 - 2008 (%)**
0 - 75 m										
Vegetation	7.8	35.1	1.6	4.1	0.1	2.6	0.0	0.0	9.5	-57
Barren land	2.5	11.2	23.3	58.3	1.4	63.8	21.4	26.2	48.6	22
Urban areas	0.9	3.8	3.2	8.1	0.4	15.9	0.8	0.9	5.2	138
Water	0.0	0.0	1.1	2.8	0.1	3.3	46.5	56.9	47.7	-42
Cloud	11.1	49.8	10.7	26.8	0.3	14.4	13.0	15.9	35.1	
Total 2005	22.2	100	40	100	2.2	100	81.7	100		
75 - 225 m										
Vegetation	40.1	41.9	27.3	25.1	1.5	12.2	0.8	1.3	69.7	-27
Barren land	11.9	12.4	36.6	33.6	3.5	28.9	32.6	56.9	84.6	-22
Urban areas	4.0	4.1	16.8	15.5	3.2	26.5	2.0	3.4	26.0	112
Water	0.0	0.0	0.2	0.2	0.0	0.0	20.1	35.1	20.3	-64
Cloud	39.8	41.5	27.8	25.6	4	32.4	1.9	3.3	73.5	
Total 2005	95.9	100	108.7	100	12.2	100	57.3	100		
225 - 525 m										
Vegetation	106.4	54.2	103.8	40.3	5.4	21.3	0.7	2.8	216.4	10
Barren land	19	9.6	81.3	31.6	5.8	23	8.8	37.8	115	-55
Urban areas	8	4.1	15.2	5.9	4.3	16.8	0.8	3.6	28.3	11
Water	1.0	0.5	1.4	0.6	0.1	0.3	10.2	43.7	12.7	-46

2008	2005									
	Vegetation		**Barren Land**		**Urban**		**Water**		**Total 2008**	**Relative change**
	(ha)	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**2005 - 2008 (%)**
Aquaculture	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	
Cloud	62.1	31.6	55.8	21.6	9.8	38.6	2.8	12.1	130.6	
Total 2005	196.5	100	257.6	100	25.5	100	23.4	100		
525 - 1000 m										
Vegetation	195.4	57.9	98.7	38.5	6.8	18.8	1.2	5.6	302.1	-10
Barren land	32.4	9.6	81.7	31.9	13.2	36.5	1.6	7.9	128.9	-50
Urban areas	7.5	2.2	12.4	4.8	7.1	19.6	0.0	0.1	27	-25
Water	1.1	0.3	1.0	0.4	0.5	1.3	8.7	42.2	11.1	-46
Aquaculture	0.1	0.0	6.4	2.8	0.1	0.2	0.0	0.0	6.5	
Cloud	101.2	30.0	56.5	22.0	8.5	23.6	9.1	44.1	175.3	
Total 2005	337.7	100	256.6	100	36.2	100	20.5	100		

Recovery rates for land cover types in the study area from the change detection analysis are shown in **Tables 5** and **6**. The recovery trend since 2005 - 2013 was divided into 2 periods: 2005 to 2008, and 2008 to 2013. The first period, from 2005 to 2008, is detailed in **Table 5**. Three years post-tsunami, water bodies slowly decreased in all buffer zones, whereas barren land areas increased by 22 % in the most seaward zone.

According to Choowong [13], beach areas at Khuk Khak and Bang Niang of Khao Lak recovered gradually within 2 years after the tsunami. Urban areas notably increased within a distance of 525 m from shoreline. In a study by Wong [31], it was reported that the tourist industry in Khao Lak had not fully recovered since the 2004 tsunami. Nevertheless, vegetated areas were deceased in 2008. The decrease seems to be a result of detection errors caused by cloud cover, as cloud areas in the 2008 image covered about 38 % of vegetation in all buffer zones.

From 2008 to 2013 (**Table 6**), there was an increase of barren land (44 %), while water areas declined by 53 %, and changed to barren land areas in the first buffer zone. Earlier work by Choowong [13] noted that the recovery of beaches near tidal channels did not recover uniformly, and will likely take several decades. Barren land area recovery at Khao Lak was slow but steady, starting with 2003, pre tsunami (110.3 ha), hitting its lowest point in 2005 (40 ha), but gradually rising in 2008 (48.6 ha) and finally to near pre tsunami levels in 2013 (69.8 ha), while water bodies decreased by more than 50 %. Overall, urban areas increased 72 to 258 % in all buffer zones, and aquaculture areas increased to a similar area as in 2013; 7.3 and 9 ha in the third and fourth buffer zones, respectively.

Table 6 Confusion matrix for the land cover changes from 2008 to 2013.

2013	2008 Vegetation (ha)	Vegetation (%)	Barren Land (ha)	Barren Land (%)	Urban (ha)	Urban (%)	Water (ha)	Water (%)	Aquaculture (ha)	Aquaculture (%)	Total 2013 (ha)	Relative change 2008 - 2013 (%)
0 - 75 m												
Vegetation	7.1	74.7	1.7	3.6	0.9	16.5	0.05	0.1	-	-	9.8	2
Barren land	0.6	6.2	39.6	81.5	2.2	42.7	27.4	57.4	-	-	69.8	44
Urban areas	1.8	19.1	5.0	10.3	2.1	40.8	0.0	0.0	-	-	9.0	72
Water	0.0	0.0	2.2	4.6	0.0	0.0	20.2	42.4	-	-	22.5	-53
Total 2008	9.5	100	48.6	100	5.2	100	47.7	100	-	-		
75 - 225 m												
Vegetation	53.5	76.8	21.5	25.4	6.3	24.2	0.2	0.9	-	-	81.0	14
Barren land	4.3	6.1	41.9	49.6	5.7	21.8	13	63.8	-	-	64.8	-23
Urban areas	11.8	17	20.9	24.7	13.8	53.2	0.3	1.7	-	-	46.9	80
Water	0.1	0.1	0.2	0.3	0.2	0.8	6.8	33.6	-	-	7.4	-64
Total 2008	69.7	100	84.5	100	26	100	20.3	100	-	-		
225 - 525 m												
Vegetation	176.3	81.5	48.7	42.4	6.4	22.6	1.8	14.1	0.000	0.0	233.2	8
Barren land	15.7	7.2	24.5	21.3	4.0	14	3.9	30.3	0.003	6.5	48	-58
Urban areas	23.3	10.8	33.7	29.3	15.7	55.4	2.0	15.6	0.014	30.4	74.6	164
Water	1.1	0.5	1.9	1.7	1.2	4.1	5.1	40.0	0.000	0.0	9.3	-27
Aquaculture	0.0	0.0	6.2	5.4	1.1	4	0.0	0.0	0.029	63.0	7.3	15,632
Total 2008	216.4	100	115	100	28.3	100	12.7	100	0.046	100		
525 - 1000 m												
Vegetation	237.5	78.7	63.1	49.0	5.0	18.7	2.7	24.0	0.2	2.6	308.5	2
Barren land	29.1	9.7	17.8	13.8	2.9	10.8	0.8	7.5	1.6	23.8	52.2	-59
Urban areas	32.8	10.9	42.6	33.1	18.4	68.3	2.1	18.8	0.6	9.7	96.5	258
Water	2.2	0.7	1.1	0.8	0	0.2	5.5	49.7	0.0	0.0	8.8	-21
Aquaculture	0.2	0.1	4.2	3.2	0.6	2.1	0.0	0.0	4.2	63.9	9.0	39
Total 2008	301.8	100	128.7	100	26.9	100	11.1	100	6.5	100		

Conclusions

This paper presents a novel change detection study, using remote sensing to assess spatial-temporal trends of land cover types of the coastal tourism zone of Khao Lak. Reported findings provide new knowledge for better understanding tsunami impacts along the shoreline. Urban areas were the most significantly impacted land cover type across all buffer zones to 1 km landward, but especially within 225 m of the shoreline. Short-term recovery is shown by the reduction of water bodies at 75 m from shore, of which some of were turned into barren land in 2008. Over the long-term, in the most seaward zone, barren land had returned to its original area of coverage, mainly due to water areas decreasing. Furthermore, urban areas increased across all buffer zones between 2008 and 2013.

The study showed that variables, such as bathymetry, coastal topography, and vegetation type, did not significantly influence the severity of the tsunami. The study's methodology enables detection of land cover types impacted by the tsunami; however, there is still need to evaluate findings over the longer term, with additional images of equivalent spatial resolution. The temporal period analysed was limited due to the limited availability of quality imagery, but resolved by pan-sharpening of THEOS imagery. For future work, it is recommended that SAR and radar be used to overcome cloud obstruction.

Some limitations in the study were observed. Firstly, the study used high-resolution pan-sharpened imagery for ground truth information, given the lack of ground truth points from field surveys in the past (2003, 2005, and 2008). The availability of pan-sharpened imagery for the study area facilitated the groundtruthing process for assessing the accuracy of the classification results. Secondly, there was discolouration after pan-sharpening of multispectral THEOS imagery, which affected classification accuracy. To reduce color distortion, and improve quality, an alternative method would be to use the IHS (Intensity-Hue-Saturation) pan-sharpening method.

Information generated from this study could be useful for supporting decision making in relation to preparedness and mitigation planning in coastal zones. This study could also be useful when dealing with future hazard events because it could influence current decisions on safe placement of urban zones and provide baseline information for further studies aimed at ascertaining appropriate setback lines for coastal zone management.

Acknowledgements

This study was partially supported by the National Research Council of Thailand, under a Thai-German Research Cooperation (NRCT-DFG) Grant under the project "Development of guidelines to assess coastal community risk and vulnerability to tsunami disaster in Phang Nga province"; and the 90th Anniversary of Chulalongkorn University Fund (Ratchadaphiseksomphot Endowment Fund). THEOS images were acquired from the image archives of Geo-Informatics and Space Technology Development Agency (Public Organization), Thailand. We also would like to thank Dr. R. Cooper for assistance with English, A. Tiangtrong and the Southeast Asia START Regional Centre (SEA START RC) team at Chulalongkorn University for their assistance in field survey.

References

[1] C Thanawood, C Yongchalermchai and O Densrisereekul. Effects of the December 2004 tsunami and disaster management in southern Thailand. *Sci. Tsunami Hazards* 2006; **24**, 207-17.

[2] E Calgaro and K Lloyd. Sun, sea, sand and tsunami: Examining disaster vulnerability in the tourism community of Khao Lak, Thailand. *Singapore J. Trop. Geogr.* 2008; **29**, 288-306.

[3] P Willroth, J Revilla Diez and N Arunotai. Modelling the economic vulnerability of households in the Phang-Nga Province (Thailand) to natural disasters. *Nat. Hazards* 2011; **58**, 753-69.

[4] T Rossetto, N Peiris, A Pomonis, SM Wilkinson, ED Del, R Koo and S Gallocher. The Indian ocean tsunami of December 26, 2004: Observations in Sri Lanka and Thailand. *Nat. Hazards* 2007; **42**, 105-24.

[5] N Tanaka, Y Sasaki, MIN Mowjood, KBSN Jinadasa and S Homchuen. Coastal vegetation structures and their functions in tsunami protection: experience of the recent Indian Ocean tsunami. *Landsc. Ecol. Eng.* 2007; **3**, 33-45.

[6] M Papathoma, D Dominey-Howes, Y Zong and D Smith. Assessing tsunami vulnerability, an example from Herakleio, Crete. *Nat. Hazards Earth Syst. Sci.* 2003; **3**, 377-89.

[7] G Kaiser, L Scheele, A Kortenhaus, F Lovholt, H Romer and S Leschka. The influence of land cover roughness on the results of high resolution tsunami inundation modeling. *Nat. Hazards Earth Syst. Sci*. 2011; **11**, 2521-40.

[8] D Kamthonkiat, C Rodfai, A Saiwanrungkul, S Koshimura and M Matsuoka. Geoinformatics in mangrove monitoring: damage and recovery after the 2004 Indian Ocean tsunami in Phang Nga, Thailand. *Nat. Hazards Earth Syst. Sci*. 2011; **11**, 1851-62.

[9] H Romer, J Jeewarongkakul, G Kaiser, R Ludwig and H Sterr. Monitoring post-tsunami vegetation recovery in Phang-Nga province, Thailand, based on IKONOS imagery and field investigations - A contribution to the analysis of tsunami vulnerability of coastal ecosystems. *Int. J. Remote Sens.* 2012; **33**, 3090-121.

[10] S Chutiratanaphun, R Boonsin, P Kuneepong and J Suttirod. Land use/land cover change by tsunami 2004 in Thailand: A case study at Phi Phi Island, Krabi Province and Ban Num Kem Village, Pang Nga Province. *In*: Proceedings of the 2nd International Conference on Information Systems for Crisis Response and Management, Brussels, Belgium, 2005, p. 301-3.

[11] SE Chang, BJ Adams, J Alder, PR Berke, R Chuenpagdee, S Ghosh and C Wabnitz. Coastal ecosystems and Tsunami protection after the December 2004 Indian Ocean Tsunami. *Earthq. Spectra* 2006; **22**, 863-87.

[12] G Kaiser, B Burkhard, H Römer, S Sangkaew, R Graterol, T Haitook and D Sakuna-Schwartz. Mapping tsunami impacts on land cover and related ecosystem service supply in Phang Nga, Thailand. *Nat. Hazards Earth Syst. Sci.* 2013; **13**, 3095-111.
[13] M Choowong, S Phantuwongraj, T Charoentitirat, V Chutakositkanon, S Yumuang and P Charusiri. Beach recovery after 2004 Indian Ocean tsunami from Phang-nga, Thailand. *Geomorphology* 2009; **104**, 134-42.
[14] GR Allen and GS Stone. Rapid assessment survey of tsunami-affected reefs of Thailand. Final Technique Report, 15 November 2005. Boston: New England Aquarium, 2005. Available at: http://neaq.org/documents/conservation_and_research/global_change/tsunami_report.pdf, accessed April 2015.
[15] C Giri, Z Zhu, LI Tieszen, A Singh, S Gillette and JA Kelmelis. Mangrove forest distributions and dynamics (1975-2005) of the tsunami-affected region of Asia. *J. Biogeogr.* 2008; **35**, 519-28.
[16] H Romer, G Kaiser, H Sterr and R Ludwig. Using remote sensing to assess tsunami-induced impacts on coastal forest ecosystems at the Andaman Sea coast of Thailand. *Nat. Hazards Earth Syst. Sci.* 2010; **10**, 729-45.
[17] P Sirikulchayanon, W Sun and TJ Oyana. Assessing the impact of the 2004 tsunami on mangroves using remote sensing and GIS techniques. *Int. J. Remote Sens.* 2008; **29**, 3553-76.
[18] RK Turner, S Subak and WN Adger. Pressures trends and impacts in coastal zones: Interactions between socioeconomic and natural systems. *Environ. Manage*. 1996; **20**, 159-73.
[19] C Small and RJ Nicholls. A global analysis of human settlement in coastal zones. *J. Coast Res.* 2003; **19**, 584-99.
[20] M Fasona and A Omojola. Land cover change and land degradation in parts of the southwest coast of Nigeria. *African J. Ecol.* 2009; **47**, 30-8.
[21] KJ Mard, A Skelton, M Sanden, M Ioualalen, N Kaewbanjak, N Pophet and AV Matern. Reconstructions of the coastal impact of the 2004 Indian Ocean tsunami in the Khao Lak area Thailand. *J. Geophys. Res. Oceans* 2009; **114**, C10023.
[22] O Rozenstein and A Karnieli. Comparison of methods for land-use classification incorporating remote sensing and GIS inputs. *Appl. Geogr.* 2011; **31**, 533-44.
[23] CA Laben and BV Brower. Process for enhancing the spatial resolution of multispectral imagery using pan-sharpening. 2000, U.S. Patent 6,011,875.
[24] A Aiazzi, S Baronti, M Selva and L Alparone. Enhanced Gram-Schmidt spectral sharpening based on multivariate regression of MS and pan data. *In*: Proceeding of the Geoscience and Remote Sensing Symposium, IGARSS. IEEE International Conference. Available at: http://www.atsdr.cdc.gov/toxprofiles/tp75.pdf, accessed October 2014.
[25] T Das. 2009, Land Use Land Cover Change Detection: an Object Oriented Approach Munster, Germany. Msc Thesis, Institute for Geo informatics, University of Munster, Germany.
[26] J Rogan and D Chen. Remote sensing technology for mapping and monitoring land-cover and land-use change. *Prog. Plan.* 2004; **61**, 301-25.
[27] United States Environmental Protection Agency (EPA). An accuracy assessment of 1992 Landsat-MSS derived land cover for the upper San Pedro watershed (U.S./Mexico). Available at: http://www.epa.gov/esd/land-sci/pdf/epa600r02040.pdf, accessed March 2015.
[28] JR Jensen. *Introductory Digital Image Processing a Remote Sensing Perspective*. 3rd ed. Prentice-Hall, New Jersey, 2005.
[29] M Kaplan, FG Renaud and G Lüchters. Vulnerability assessment and protective effects of coastal vegetation during the 2004 Tsunami in Sri Lanka. *Nat. Hazards Earth Syst. Sci.* 2009; **9**, 1479-94.
[30] S Günthert, M Wieland and A Siegmund. Change detection analysis for assessing the vulnerability and protective effect of beach forests in case of the tsunami 2004 in Thailand. *Photogramm Fernerkun* 2011; **4**, 247-60.
[31] PP Wong. Impacts, recovery and resilience of Thai tourist coasts to the 2004 Indian Ocean Tsunami. *Geol. Soc. London Spec. Publ.* 2012; **361**, 127-38.