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Assessment of Natural Hazard Damage and Reconstruction: A Case Study from Band Aceh, Indonesia

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Abstract

There is an increasing interest in assessing the strengths and weaknesses of remote sensing imagery and geographic information system products as they relate to estimating populations at risk before, during, and after natural hazards. This research examines the spatial and temporal effectiveness of satellites and extent of damage products that were created for Banda Aceh, Indonesia after the 26 December 2004 tsunami. SPOT, FORMOSAT, MODIS and Landsat ETM+ imagery provided high temporal resolution data within three days of the tsunami. However, high-resolution commercial satellites (Quickbird, IKONOS) provide the most accurate data that can be used to assess infrastructure damage in cities like Banda Aceh before and after natural disasters. Of the six extent of damage products (USAID, USGS, Dartmouth Flood Observatory, DLR, SERTIT, DPRC) created after the tsunami, DLR provided the most accurate data on the extent of damage in Banda Aceh (94% agreement with Quickbird imagery). When these products are combined with population data estimates of populations at risk can be created to identify the areas most severely affected by a natural disaster. Pre-tsunami and post-tsunami imagery combined with imagery collected two and a half years after the tsunami show an extensive reconstruction of structures. Satellite imagery and geographic information system methods used in this research are most effective in regions where field data is sparse or difficult to collect within the first week following a natural disaster.

Keywords *geographic information systems, natural hazards, satellite imagery, tsunami*

Introduction

Floods are the most frequent and devastating of all natural hazards and cause extensive damage to infrastructure and agriculture (Sanyal and Lu 2004). Urban landscapes are especially vulnerable to damage by floods because they are composed of many different types of material arranged in intricate ways (van der Sande et al. 2003). Tsunamis serve as a major cause of flooding and often cause extensive damage to coastal communities (Adger et al. 2005). The tsunami associated with the 26 December 2004 (hearinafter 12/26) Sumatra-Andaman earthquake killed an estimated 283,000 people along the coastlines of the Indian Ocean (Lay et al. 2005). Indonesia was the country most devastated by the tsunami with some 160,000 Indonesians killed and another 30,000 missing (Doocy et al. 2007; Frankenberg et al. 2008).

The 12/26 Indian Ocean tsunami was unique in the scope and scale of a contemporary natural hazards research due to the outpouring of satellite imagery made publicly available after the event (Allenbach et al. 2005; Chen et al. 2005). Moderate and high-resolution satellite imagery was widely employed in assessing damage caused by the 12/26 Indian Ocean tsunami (Borrero 2005; Chen et al. 2005; Ghosh et al. 2005; Miura et al. 2006, Belward et al. 2007; Liu et al. 2007). Remote sensing imagery also played an important role in both the post-disaster response and predictive modeling of extent of damage by comparing imagery acquired before the natural disaster (Brivio et al. 2002; Borrero 2005; Tralli et al. 2005). However, there still has not been an extensive study of the temporal and spatial resolution of remote sensing imagery available after the tsunami and it is currently important to quantify the near real-time potential of different sensors (Belward et al. 2007; National Research Council 2007).

There is also an increasing interest in assessing the strengths and weaknesses of estimating geographical information system products created after a natural hazard, especially as it relates to estimating the population of communities at risk (Belward et al. 2007; National Research Council 2007). Regional disaster centers have been developed that provide local, state, federal, and regional emergency managers with geographical information system products and tools to aid in response and recovery (Laben 2002; National Research Council 2007). Rapid mapping service from the United States of America (i.e. United States Agency for International Development (USAID), United States Geological Survey (USGS), Dartmouth Flood Observatory), Europe (i.e. Deutsches Zentrum für Luft- und Raumfahrt (DLR), Service Régional de Traitement d'Image et de Télédétection (SERTIT)), and Asia (i.e. Disaster Prevention Research Centre (DPRC)) have led the way in providing products to help in disaster management and humanitarian projects in the Pacific region (Allenbach et al. 2005; Liu et al. 2007). However, there has been relatively little research that compares and quantifies the accuracy of these products (Belward et al. 2007). Indeed, identifying the strengths and weakness of geographical information system products before the next near-global natural hazard may provide insight into improvements that can be incorporated into regional disaster center protocols and improve our ability to assess and organize relief efforts and monitor reconstruction (Culter 2003).

This research has three primary objectives. First, we compare satellites used to assess damage after a natural hazard and near real-time accuracy using Banda Aceh, Indonesia as a case study. Second, we test the accuracy of the geographical information system products created after the 12/26 tsunami to quantify the extent of damage and populations at risk in Banda Aceh. Third, we examine the utility of high-resolution imagery to identify possible advances in the assessment of damage and reconstruction after natural disasters.

METHODS

Study Area

This research focuses on Banda Aceh, located in northern Sumatra, Indonesia (Figure 1). Banda Aceh is the provincial capital and largest city in the province of Aceh with a population of approximately 260,000 people (Davies 2006). The Sultanate of Aceh was the first Islamic state in Southeast Asia and there has been a long history of conflict between people in the region and the Dutch and Indonesia governments due to Banda Aceh's strategic location and natural resources, such as oil and natural gas. Before the tsunami, civil strife between the Indonesian Government and groups such as the Free Aceh Movement made it nearly impossible to travel or collect data in the region. This conflict has resulted in the death of an estimated 15,000 local people and troops (Davies 2006).

Remote Sensing Imagery

Remote sensing imagery used in the assessment of the 12/26 tsunami was collected for Banda Aceh, Indonesia. We undertook extensive literature reviews to identify research related to the assessment of damage in Indonesia and data available from organizations dedicated to research and analysis support to help in disaster management and humanitarian projects (Borrero 2005; Chen et al. 2005; Ghosh et al. 2005; Miura et al. 2006; Belward et al. 2007; Yang et al. 2007). Nine remote sensing datasets were identified as having contributed to the assessment of damage after the 12/26 tsunami including Landsat 7, SPOT 2 and 5, EOS MODIS and ASTER, FORMOSAT 2, EROS A, IKONOS 2 and QuickBird. Imagery from these satellites for Banda Aceh was collected from the United States Geological Survey EROS Datacenter, Pacific Disaster Center, and international organizations. Three QuickBird scenes of Banda Aceh were purchased from Digital Globe for 23 January 2004, 28 December 2004, and 30 July 2007. These time periods correspond to pre-tsunami (eleven months before the tsunami), post-tsunami (two days after the tsunami) and the reconstruction phase (two years and six months after the tsunami).

Geographic Information System Products

After the 12/26 tsunami, a number of agencies created extent of damage products for the region in geographical information system formats. The best and most widely accessibly were from the USGS, Dartmouth Flood Observatory, USAID, Germany's DLR, France's SERTIT and Taiwan's DPRC. The USGS used Landsat ETM+ images from before and after the tsunami to estimate the extent of damage in Sumatra and Banda Aceh. The Dartmouth Flood Observatory estimated the flood inundation limit in Sumatra using MODIS imagery. USAID used SPOT imagery to estimate the extent of damage in Sumatra. DLR used Landsat 7 ETM+ and UK-DMC Surrey Linear Imager to estimate the extent of damage in Sumatra. SERTIT used SPOT 5 imagery to estimate the extent of damage four classes (devastated urban area, highly effected urban area, affected urban area, and not affected urban area) for Banda Aceh (Allenbach et al. 2005). DPRC used FORMOSAT 2 imagery to estimate extent of damage in Banda Aceh (Liu et al. 2007). All products were downloaded and subsets of the Banda Aceh area were georectified in World Geodetic System (WGS84) using ArcMap 9.2 (ESRI, Redlands, CA).

Population and elevation data were also acquired to assess the extent and severity of damage in Banda Aceh. Raster population data from the LandScan 2002 were downloaded for the region. This worldwide population database is based on a 30" x 30" latitude/longitude grid, with each cell holding the number of people contained in the cell based on sub-national censuses provided by the International Programs Center of the Population Division of the U.S. Census Bureau combined with NASA's Earth Observing System (EOS) MODIS land cover database.

The digital elevation model (DEM) used in this analysis was an elevation raster obtained from the Shuttle Radar Topography Mission (SRTM). The SRTM data was created using a radar system on the Space Shuttle Endeavor in 2000 and this near global scale dataset has a cell size of 90 m x 90 m. While data obtained in the SRTM raster file is accurate to within sixteen meters of the actual elevation, there are "no-data" pockets in the raster where water or highly-shadowed locations prevented the radar calculation from being successfully executed (Sun et al. 2003). A Spatial Analyst's Raster Calculator into ArcMap 9.2 was used to remove all negative values in the raster, eliminating the false values given in the SRTM and coding them as voided cells in the raster. Following this, the elevation data were patched using Spatial Analyst's Focal Statistics to carry out a neighborhood analysis. In this process, the values of cells neighboring each voided cell (6 x 6 cells) are averaged to calculate a value for the voided cell, resulting in a new raster. The elevation data was then clipped using Global Self-consistent, Hierarchical, High-resolution Shoreline shapefile to get rid of calculated values that were outside of the boundaries of Banda Aceh.

Data Analysis

Remote sensing imagery was assessed by comparing temporal and spatial effectiveness of each satellite and sensor. Temporal resolution was assessed based on the date that imagery of Banda Aceh was captured after the 12/26 tsunami. Spatial effectiveness was based on the pixel size and the subsequent ability of the imagery to identify USGS land-cover classification levels I, II, III, or IV (Jensen 2000). QuickBird imagery (0.61 m pixel resolution) and field surveys in

December 2008 were used as reference data. The cost of imagery for Banda Aceh as of December 2004 was also quantified in US dollars.

The area and extent of damage products for Banda Aceh were compared to extent of damaged structures digitized within QuickBird imagery (Miura et al. 2006). The aerial extent of damage for each product was digitized and calculated in ArcMap 9.2. Agreement, errors of omission (damaged areas incorrectly classified as undamaged) and commission (undamaged areas incorrectly classified as damaged) as compared with QuickBird imagery were calculated for each extent of damage product (Bleward et al. 2007). Estimates of extent of damage were also combined with global population data to identify the number of individuals affected by the tsunami according to 2002 LandScan population estimates and number of individuals severely affected based on populations at or below five meters above sea level. The Quickbird extent of damage was then quantified into three classes following Miura et al. 2006: completely destroyed, heavy to moderate damage, and slight damage for Banda Aceh. The three classes were overlaid on the population raster.

QuickBird scenes from 23 January 2004, 28 December 2004, and 30 July 2007 were imported into ArcMap 9.2 and georectified to pre-tsunami imagery using ground control points such as buildings and landmarks that remained standing even after the tsunami. The rooftops of each individual building were digitized as polygons to calculate the area of each building. A high-resolution analysis of roof type and building type was undertaken for a 500 meter by 500 meter area within the center of Banda Aceh. The roof type was divided into five categories: metal roofs, distinguished by their high reflectance or rusting roofs, tiles roofs with their distinctive coloration, construction sites, distinguished by the lack of roofing (prior and post tsunami only), mosques, and uncertain. Building type was divided into three categories:

residential housing with a general small rectangular shape, commercial or government building with an elongated rectangular shapes, and large upscale homes with irregular footprints. We compare the extent of building before, after, and two and a half years after the tsunami using T-Tests to determine if there were significant differences.

Results

Assessment of Satellite Imagery

There were significant differences in the temporal and spatial resolution of imagery available after the 12/26 tsunami (Table 1). SPOT 2 imagery was available two hours and twenty minutes after the tsunami hit Banda Aceh while FORMOSAT 2 and QuickBird captured high-resolution imagery two days after the tsunami (Figure 2A,B). IKONOS, Landsat ETM+, and MODIS all captured imagery of Banda Aceh three days after the tsunami Figure (Figure 2 C). SPOT 5 and EROS A captured imagery four days after the tsunami and ASTER imagery was available twenty six days after the tsunami (Figure 2D, E). QuickBird and IKONOS provided the highest resolution imagery to USGS land-cover classification level IV (i.e. houses, cars, boats). FORMOSAT 2, EROS 2, and SPOT 5 provided high-resolution imagery to USGS land-cover classification level III (i.e. single family residential, commercial buildings, transportation). SPOT 2 and ASTER provided imagery to level II (i.e. residential, commercial, industrial) and MODIS and Landsat ETM+ to level I (i.e. urban, barren land).

Assessment of GIS Products

Six extent of damage geographical information products were available three weeks after the tsunami (Figure 3). When these were compared to the extent of damage from digitized

QuickBird imagery from Banda Aceh (53.60 km^2) there were significant differences in the extent and shapes of each product (Table 2). Dartmouth Flood Observatory and DPRC were the first extent of damage products publicly available three days after the tsunami. However the Dartmouth Flood Observatory had the lowest agreement (65%) and underestimated the extent of damage while the DPRC had the second lowest agreement (78%). USAID and SERTIT products were available eight and ten days after the tsunami and these products had relatively similar levels of agreement (83% and 82% respectively) and relatively low commission and omission errors. The DLR extent of damage product was available twelve day after the tsunami and was the most accurate with high agreement (94%) and low commission and omission errors. The USGS products were available twenty days after the tsunami with high agreement (91%) but the USGS product had the highest commission error and tended to overestimate the extent of damage.

When extent of damage products were combined with population and elevation geographic information system data, there were differences in estimates of population affected (Table 3). Products from the Dartmouth Flood Observatory, DLR, and DPRC appear to underestimate the population affected by the tsunami while USGS, USAID, and SERTIT appear to overestimate the population affected by the tsunami. The numbers of individuals severely affected by the tsunami ($\leq$ 5m above sea level) are relatively similar with the exception of the Dartmouth Flood Observatory. When the QuickBird extent of damage product in three classes are combined with population for all of Banda Aceh, this provides an example of products theoretically available for relief efforts after a natural hazard such as floods or tsunamis (Figure 4).

Monitoring Reconstruction

QuickBird imagery can be used to compare the extent of building before, immediately after, and two and a half years after the tsunami (Figure 5). There were 699 buildings identified in the subset region of Banda Aceh, 85 percent of which were residential homes with a mean area of 107.5 m^2 and metal roofs (Table 4). After the tsunami 96 percent of the structures were destroyed. There was no significant difference between building area and survival of the structures. Indeed, structures destroyed were significantly larger than surviving structures (T-Value = 7.49, $P < 0.001$, DF = 34). Two and a half years after the tsunami there has been significant reconstruction (Figure 6). There were 585 structures constructed after the tsunami, seventy-four of which were still under construction at the time of image acquisition. Most of the reconstruction was of residential homes that were significantly smaller in area than pre-tsunami structures (T-Value = 9.62, $P < 0.001$, DF = 1262). There was also a relative increase in the use of tiles for roofing material and a relative decrease in large up-scale homes and commercial buildings.

Discussion

The 12/26 tsunami has had immense consequences in both the short and long term for the population of Banda Aceh and for the natural and man-made environment. In response to the physical damage and human suffering, national and international groups poured significant resources, personnel, and money into the region. Indeed, it is estimated that by 2006, 6.4 billion dollars had been given in government aid (2 billion from the European Union alone) and 1.7 billion had come from private donors to the global relief and reconstruction effort (ESRI 2006).

These inflows afforded an unprecedented opportunity to rebuild Banda Aceh and were at least part of the reason that the civil war in Aceh ended in 2005 (Davies 2006).

Assessment of Satellite Imagery

The ability to assess the extent of natural hazards in near real-time is extremely important for planning relief efforts especially in remote regions or regions where little data is available like Banda Aceh (National Research Council 2007). Cloud cover not withstanding, MODIS has an advantage for comparing moderate resolution satellites within a twenty-four hour (two images captured) and forty eight hour period (four images captured) after a natural hazard at a no cost. MODIS has been estimated to be within 17 percent accuracy of Landsat ETM+ estimates of damage (Belward et al. 2007) and has also been used to develop a damage classification scheme for communities in Sumatra based on the extent of bare earth around point locations (Frankenberg et al. 2008). However, MODIS imagery cannot classify below USGS land-cover classification level I and appears to consistently underestimate the extent of areas damaged and is thus most useful at a regional scale but of limited use for urban areas.

Within three days of the tsunami, other earth observation satellites with multi-directional sensors such as FORMOSAT 2, SPOT 2 and 5 captured images of Banda Aceh. This imagery is accurate to USGS land-cover classification II and III and is useful in the organization of relief efforts by raising public awareness of the damage and for relief efforts in identifying the extent of damage to infrastructure such as bridges and residential structures by neighborhood (Liu et al. 2007). Even with the Landsat ETM+ line drop malfunction of May 31, 2003 that ended thirty-one years of continuous Landsat series data, the sensor is still useful in assessing the extent of damage (Belward et al. 2007). ASTER imagery, an on-demand system, was available for Banda Aceh twenty-six days after the tsunami, too late to be of use for immediate relief efforts. Once acquired, the data successfully showed the extent of damage (Borrero 2005), however, on-demand systems are not as useful as systematic collection and distribution systems like MODIS, Landsat, and SPOT. By the year 2010, new satellites and constellations of satellites (Disaster Monitoring Constellation, Rapid Eyes, COSMO- SkyMed) will be launched specifically to study natural hazards. If these satellites are successfully launched and current sensors are operational, we estimate that five panchromatic images of 2.5 m or less and eight multi-spectral images of 10 m or less will be available daily (Gillespie et al. 2007).

Archived and acquired imagery from commercial satellites were also available within three days of the tsunami. This is the most useful for communicating to relief workers the extent of the damage and may be used to estimate individual structure damage and mortality in near real-time (Ghobarah et al. 2006). Remote sensing based on levels of house destruction has been significantly associated with mortality, however, one limitation of remote sensing research is that it cannot quantify individuals such as women, children, and the elderly, who tend to be the most vulnerable populations (Nishikiori et al. 2006; Neumayer and Plümper 2007). The cost of this imagery is significantly greater than government imagery and is best applied in urban areas with high population densities.

There was a notable lack of active spaceborne imagery such as radar used to assess the damage after the tsunami. Elevation data from SRTM data was used to model inundation distance and run-up heights well after the tsunami event (Borrero 2005; McAdoo et al. 2007). Bovolo and Bruzzone (2007) proposed a new method to automate and classify damage after the tsunami using synthetic aperture radar that has great potential for near real-time damage assessment especially if applied to the ten radar satellites that will be launched over the next three years that contain 1 m pixel sizes (SAR-Lupe, COSMO- SkyMed, TerraSAR-X) and daily coverage of the tropics. This can be used to create global benchmarks on the topography of the earth's surface and populated regions. These benchmarks can be rapidly compared to post-natural disaster imagery to assess damage in near real-time, regardless of weather conditions (Gillespie et al. 2007).

Assessment of GIS Products

Once remote sensing data is acquired, imagery must be converted into a GIS format in order to assess the extent of damage (Laben 2002; Geist et al. 2006). There can be significant lag time between when the imagery is acquired and when the GIS products are published (i.e. 3 to 20 days) and there appears to be an increase in accuracy of the extent of damage products with time. Dartmouth Flood Observatory was the first to produce estimates on the extent of damage three days after the tsunami. The Dartmouth Flood Observatory product, based on MODIS imagery, underestimates extent of damage and so should only be used as an initial assessment of damage. The DLR and USGS products were the most accurate products for Banda Aceh, followed by USAID, SERTIT, and DPRC. Although USAID and USGS outlined the extent of damage fairly well, the SERTIT product is the only one to estimate gradients of damage in Banda Aceh. These gradient maps may be the most useful in urban areas. However, it should be remembered that the SERTIT product was only available for Banda Aceh while USAID, USGS, and DLR products covered all of Sumatra.

Data on population distribution and density appear to be extremely important in estimating the extent of damage after a natural hazard (National Research Council 2007). Banda Aceh had no prior GIS estimates of population available from Indonesia, only paper land cover maps, largely due to the prior political sensitivity of the region. However, global extents of population distribution appear accurate to within 10 percent for Banda Aceh. Flood estimations of populations at risk depend primarily on the resolution of elevation data (Sanyal and Lu 2004). Methods employed to correct SRTM data should be repeated for all urban regions vulnerable to flooding prior to natural hazards in order to reduce time needed to create products. This may improve estimates of damage and populations at risk.

Commercial imagery, such as QuickBird, is extremely useful for assessing the extent of damage after a natural hazard. In Banda Aceh, the imagery clearly identifies the number of destroyed or damaged structures (Borrero 2005). It is also very useful in assessing the reconstruction process after a natural hazard. Our results suggest that a majority of the residential building were rebuilt in the same location but were significantly smaller in size and constructed of better building materials. It also suggests that an entire city the size of Banda Aceh can be digitized before and after a natural hazard event and the number, size, and types of building can be identified. In the future, commercial satellites, such as GeoEye with 0.4 m pixel size, will be the most useful for estimating extent and magnitude of damage and should be regularly employed for natural disasters in urban areas.

Conclusion

In this article we have assessed the effectiveness and accuracy of remote sensing systems and geographic information system products for providing rapid assessments of the extent of damage as well as subsequent reconstruction in Banda Aceh, Indonesia. MODIS imagery provides near-real time assessments of extent of damage, while government space agencies that manage SPOT, Landsat ETM+, and FORMOSA provide higher resolution regional scale data that can be used to create products that assess the extent of damage in a geographic information systems formats with 78 to 94 percent accuracies within two weeks of a natural hazard.

However, high resolution commercial satellite imagery from IKONOS, QuickBird, and Geoeye are the most appropriate for analysis of individual structures and have the greatest potential for assessing the extent of damage and reconstruction in urban areas. Our results clearly demonstrate advances that have been made in natural hazards research and the important role that remote sensing of natural hazards can play in understanding and reacting to disasters, particularly in isolated areas such as Banda Aceh.

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Table 1. Satellite imagery used in the assessment of the 26 December 2004 tsunami for Banda Aceh, Indonesia.

Satellite	Sensor	Pixel Size (m)	Temporal Resolution	First Image	Cost (US$)
SPOT 2	HRV	10, 20	variable	12/26/2004	6750
FORMOSAT 2	IPS	2, 8	variable	12/28/2004	3270
QuickBird	Pan, MS	0.6, 2.5	2-3 days	12/28/2004	8540
IKONOS 2	Pan, MS	1, 4	3-5 days	12/29/2004	7950
Landsat 7	ETM+	15, 28.5	16 days	12/29/2004	530
EOS	MODIS	250, 500	12 hours	12/29/2004	0
SPOT 5	PAN, HRG	2.5, 10	variable	12/30/2004	6750
EROS A		1.9	3-7 days	12/30/2004	4754
EOS	ASTER	15, 30	on demand	1/21/2005	80

Table 2. Geographic information system extent of damage products used in the assessment of the 26 December 2004 tsunami for Banda Aceh, Sumatra.

Products	Extent of Damage (km^2)	Agreement (km^2)	Commission (km^2)	Omission (km^2)	Date Available
Dartmouth Flood	43.45	34.58	8.87	17.22	12/29/2004
DPRC	51.50	42.28	9.24	9.12	12/29/2004
USAID	56.18	44.53	11.65	7.28	1/02/2005
SERTIT	61.72	44.13	17.59	9.47	1/04/2005
DLR	53.52	50.48	3.05	3.12	1/06/2005
USGS	77.33	48.61	28.72	3.20	1/14/2005

Table 3. Comparison of geographic information system extent of damage products from Banda Aceh and population affected from LandScan 2002 population data and severely affected populations based on area ≤ 5m above sea level.

Damage Products	Population Affected	Severely Affected
Dartmouth Flood	9239	3617
DPRC	12816	5177
USAID	78525	4591
SERTIT	88194	5163
DLR	15934	5324
USGS	91323	5369
QuickBird	31311	5324

Table 4. QuickBird assessment of structures in central Banda Aceh from 23 January 2004, 28 December 2004, and 30 July 2007 that correspond to pre-tsunami (11 months before tsunami), post-tsunami (two days after the tsunami), and the reconstruction phase (two years and six months after the tsunami).

Attributes	Pre-tsunami	Post-tsunami	Reconstruction Phase
Total Structures			
Total	699	27	612
Mean Area (m^2)	119	236	78
Structure Type			
Residential			
Total	595	19	562
Mean Area	107.5 (±81.1)	243.0 (±222.6)	80.2 (±75.0)
Large Upscale			
Total	92	7	47
Mean Area	183.8 (±109.5)	222.5 (±137.8)	62.4 (±50.8)
Commercial and Government			
Total	12	1	4
Average Area	238.4 (±114.5)	195.2	44.4 (±4.9)
Roof Types			
Metal			
Total	544	12	322
Mean Area	120.4 (±91.8)	267.8 (±274.6)	75.9 (±66.7)
Tile			
Total	144	14	178
Mean Area	115.5 (±88.3)	218.5 (±105.6)	90.4 (±69.4)
Under Construction			
Total	9	0	74
Average Area	113.3 (±58.4)	0	60.1 (±42.3)
Unknown/Other		1	37

Figure 1. Location of Banda Aceh, Sumatra.

Figure 2. Satellite imagery of Banda Aceh after the December 26, 2004 tsunami: a. SPOT 2, b. FORMOSAT 2, c. MODIS, d. SPOT 5, e. ASTER.

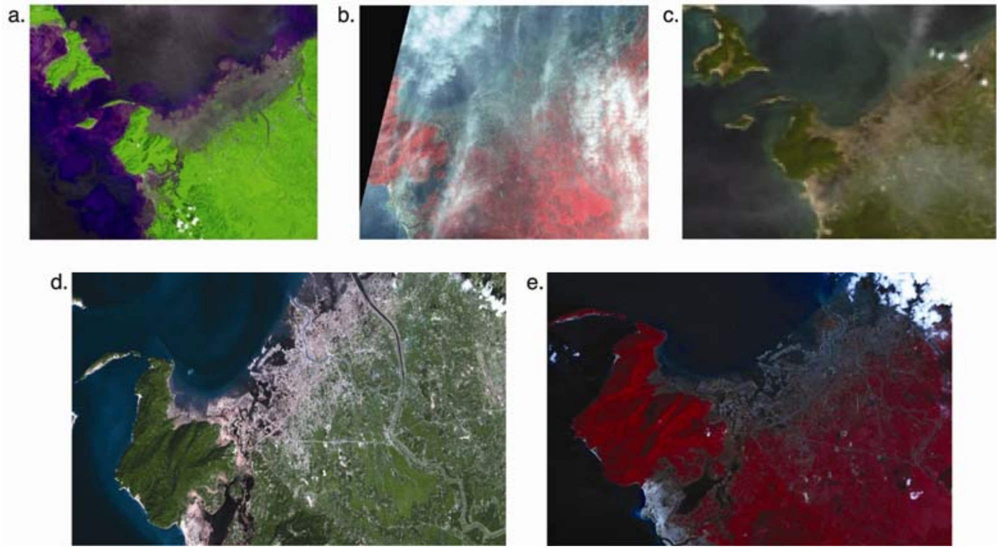
Figure 3. Geographic information system products created after the 26 December 2004 tsunami: a. Dartmouth Flood Observatory, b. Disaster Prevention Research Centre (DPRC), c. United States Agency for International Development (USAID), d. Service Régional de Traitement d'Image et de Télédétection (SERTIT), e. Deutsches Zentrum für Luft- und Raumfahrt (DLR), f. United States Geological Survey (USGS).

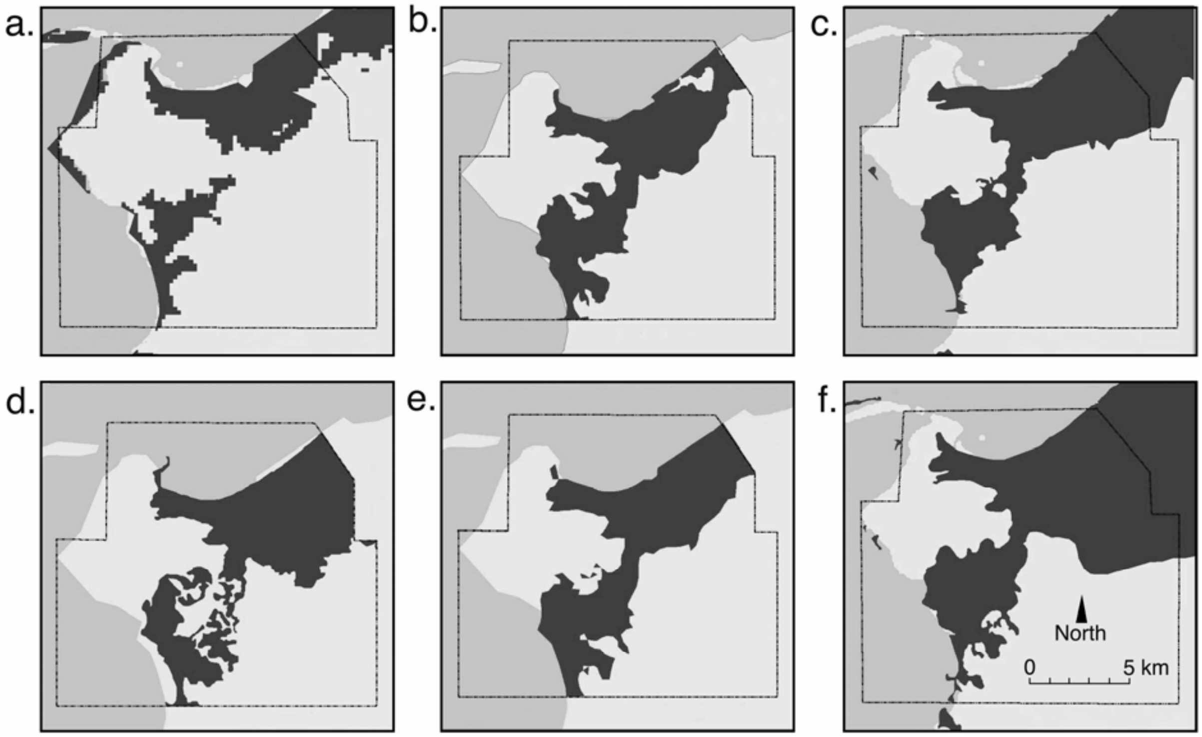
Figure 4. Damage assessment in three classes (destruction, substantial to heavy damage, slight) over QuickBird imagery and Landscan population data.

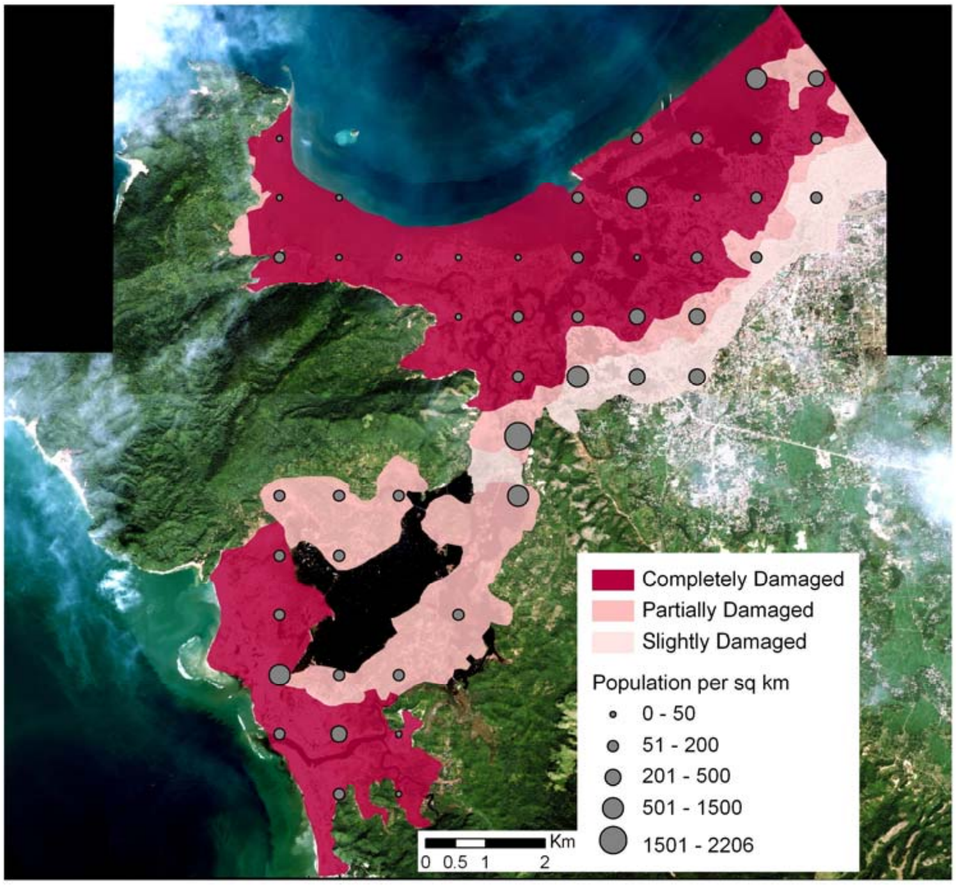
Figure 5. Samples of QuickBird imagery from before the tsunami (23 January 2004), after the tsunami (28 December 2004) and two and a half years after the tsunami (30 July 2007) for coastal Banda Aceh, Indonesia.

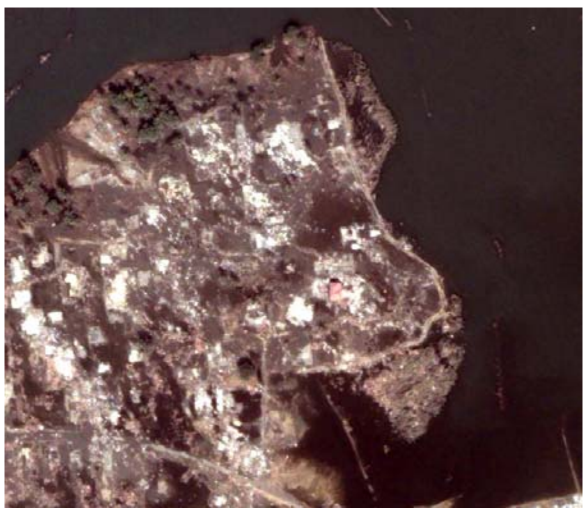
Figure 6. Geographic information system product on damage and reconstruction over QuickBird imagery of central Banda Aceh. Blue polygons are structures from before the tsunami (23 January 2004). Red polygons are structures that survived the tsunami (28 December 2004). Green polygons are structures reconstructed two and a half years after the tsunami (30 July 2007).

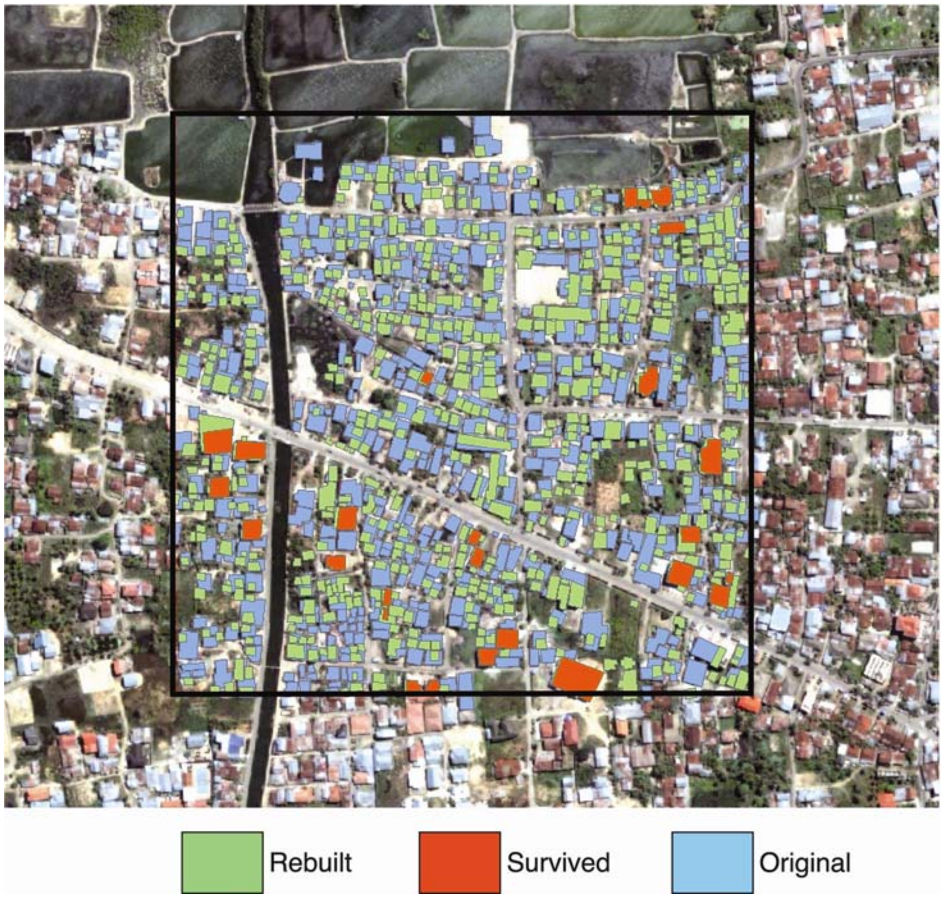

10°
South China Sea
Banda Aceh,
Indonesia
M A L A Y S I A
Borneo
0°
I N D O N E S I A
Sumatra
Indian Ocean
0
500 km
Java
100°
110°


a.
b.
c.
d.
e.


a.
b.
c.
d.
e.
f.
North
0
5 km


Completely Damaged
Partially Damaged
Slightly Damaged
Population per sq km
0 - 50
51 - 200
201 - 500
501 - 1500
1501 - 2206
0 0.5 1 2
Km




Rebuilt
Survived
Original