Mine Closure 2016 – AB Fourie and M Tibbett (eds)

doi:10.36487/ACG_rep/1608_24_Dacre

The use of satellite-based remote sensing methods to assess the changes in the environmental impacts from the Marcopper disaster on Marinduque Island, Philippines

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Abstract

The Marcopper Mining Disaster occurred between 1975 and 1996 on the Philippine island of Marinduque, a province of the Philippines. It remains one of the largest mining disasters in history and is almost completely un-rehabilitated. The Marcopper Mining Corporation mined the Mt. Tapian ore body followed afterwards by the San Antonio copper ore body, using open pit methods. Three separate environmental incidents occurred during this time which finally culminated in between 2 to 3 million tonnes of tailings which flowed from the Tapian in-pit tailings facility along a drainage tunnel into the 26 km long Boac River. Flooding isolated and buried some villages under 2 m of floodwater and tailings. Environmental impacts were considerable and the government declared the Boac River dead. Since 2002, despite two major studies which were completed in 2004 and 2005, no remediation efforts have been undertaken on any of the waste landforms or rivers to-date.

In order to understand the ongoing environmental changes taking place on the mine waste landforms, the Australian Centre of Geomechanics partnered with MacDonald, Dettwiler and Associates to undertake a preliminary review of the Marcopper waste landforms using products derived from historical radar and optical images collected over the island from the 1996 to 2014. This paper summarises the results of this study and makes recommendations for further remote sensing studies and ground-truthing activities.

Remote sensing challenges using historical data were significant and included persistent cloud cover or haze in regions, heavy vegetation in some areas, and localised steep terrain. Historical images were used to map the changes taking place on the waste landforms using a variety of remote sensing approaches including automated multi-date change detection algorithms, Normalised Difference Vegetation Index, terrain analysis and land cover mapping.

This study found that the Calancan Bay tailings outfall has retreated over 550 m since 1996 and that barren and steep-sloped regions are present near the mine pits and tailings dams. In addition, the size of both pit lakes has continued to increase. Nevertheless, the findings showed that within the vicinity of the open pits and mine waste landforms there has been gradual reestablishment of vegetation during the 18-year study period.

1 Introduction

The Marcopper Mining Disaster occurred between 1975 and 1996 on the Philippine island of Marinduque, a province of the Philippines (OXFAM 2005a). Over 200 million tonnes of contaminated mine waste was discharged from the mine site during the mine life which ranks the disaster ranks as the largest in the history of the Philippines.

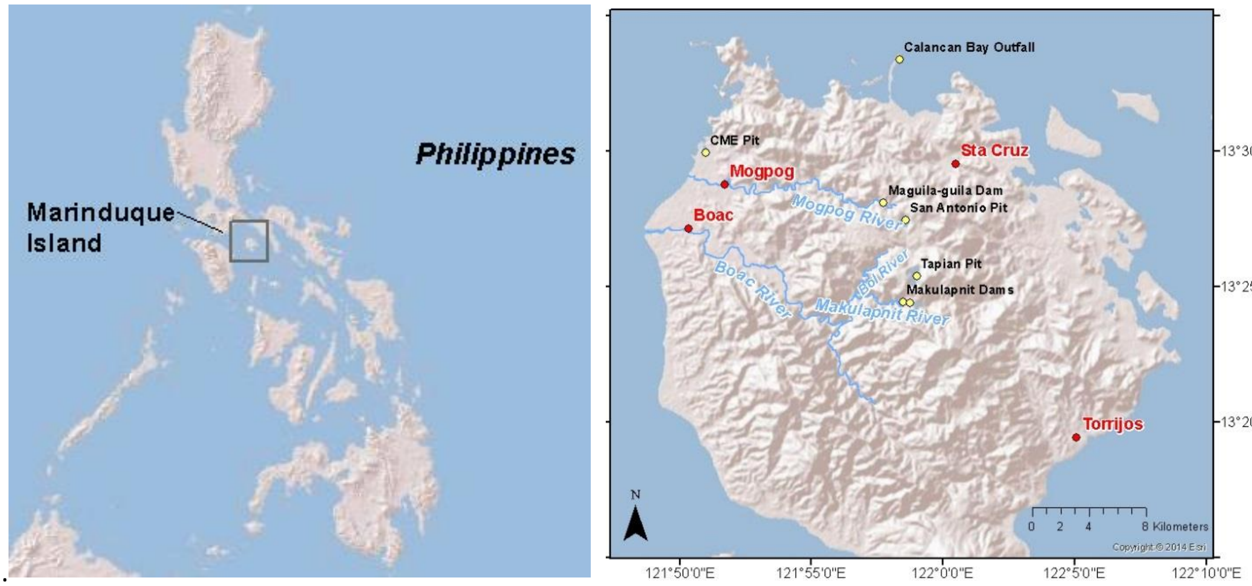
Two major independent investigations were undertaken by The Futures Group International (2004) and OXFAM (2005b) and the reports released in 2004 and 2005 respectively. The recommendations of both the reports called for the full rehabilitation of the mine site, rivers and Calancan Bay, the implementation of a comprehensive monitoring program and full compensation to the islanders affected. In 2005, experts from the United States Geological Survey (USGS) further emphasised the importance of immediately repairing the mine tailings dams in order to prevent another environmental disaster in the province. The four mine tailings dams: the Maguila-guila, Bol River Dam and the Upper and Lower Makalupnit Dams were abandoned after Marcopper ceased its operations in the country (Balaba 2005). No further remediation work has been undertaken on the tailings dams.

A further site inspection and field survey exercise was undertaken in 2012 by the Philippines Mines Geoscience Bureau (MGB) (Mojares et al. 2012). The survey exercise was undertaken to provide an update on the mining related environmental impacts of critical mine areas. Again the report recommended further monitoring, inspections and hydrological assessments related to groundwater impacts and pit lake overflow.

The Australian Centre for Geomechanics (ACG) partnered with MacDonald, Dettwiler and Associates (MDA) to undertake a preliminary review of the Marcopper waste landforms using remote sensing methods. This paper looks specifically at the environmental changes taking place on the mine waste landforms. This study consisted of deriving products from historical Synthetic Aperture Radar (SAR) and Landsat data, analysing these results, and providing recommendations to enhance further remote sensing studies or ground-truthing activities.

2 Overview of the Marcopper mining disaster

Figure 1 provides an overview of the key locations on Marinduque Island that are discussed in this paper.



(a) (b)

Figure 1 (a) Marinduque Island regional overview; and (b) locations of features discussed in this report. Background is courtesy of ESRI 2014

The Marcopper Mining Disaster occurred between 1975 and 1996 on the Philippine island of Marinduque, a province of the Philippines located in Luzon. Marcopper first mined the Mt. Tapian ore body followed afterwards by the San Antonio copper ore body, using open pit methods. During this timeframe three separate environmental incidents occurred which are summarised as follows:

- From 1975 to mid-1991, Marcopper dumped some 200 million tonnes of mine tailings via surface disposal into Calancan Bay creating a 7 km long tailings causeway. The tailings eventually covered approximately 80 km² of coral reef systems in the bay.

- The Maguila-guila sedimentation dam was built in 1991 on the Mogpog River to limit the waste rock material that was eroding from the un-rehabilitated Maguila-guila waste rock landforms and impacting the river. The dam rapidly silted up, and following heavy rains in 1993 collapsed and flooded the Mogpog River killing two people and causing significant environmental impacts.
- In March 1996, following the failure of a bulkhead in the Tapian drainage tunnel, between 2 to 3 million tonnes of tailings flowed from the Tapian in-pit tailings facility through the drainage tunnel and was discharged into the 26 km long Boac River. Subsequent flooding isolated and buried some villages under six feet of floodwater and tailings. Environmental impacts were considerable and the government ultimately declared the Boac River dead.

Since 2002 no remediation efforts have been undertaken on any of the mine sites and waste landforms.

3 Remote sensing approach

The objective of this study was to show how satellite remote sensing technology can record and quantify the rehabilitation of a mining disaster area. Marinduque presents a challenge from a remote sensing perspective for a variety of reasons mostly related to persistent cloud cover. Despite this challenge, we were able to use a variety of methods during this study, specifically:

- Collecting 30 m Landsat satellite imagery over the period of time of 1988 to present.
- Conducting a visual analysis of the imagery in areas directly impacted by the mining disasters and correlating the image dates with the mining disaster historical timeline.
- Calculating Normalized Difference Vegetation Index (NDVI) results over each year collected and comparing each year’s chlorophyll content at every pixel in the study area.
- Classifying land cover for the earliest and latest dates collected and calculating from-to change based on a change matrix.
- Performing terrain analysis on a relatively high-resolution Digital Elevation Model to prioritise areas for future monitoring.
- Integrating the layers described above to understand existing conditions and identify areas that might be considered as priorities for future monitoring.

3.1 Development of radar-derived products

The use of Interferometric Synthetic Aperture Radar (InSAR) was evaluated but there was not enough suitable historical data in archives to provide a meaningful result. InSAR is a satellite data processing technique used to map and monitor very subtle surface movement changes, both vertical (up/down) and lateral (east/west), over mine sites around the world. Therefore, to evaluate conditions on Marinduque Island, MDA created a RADARSAT-derived Digital Elevation Model (DEM). In addition to the 10 m DEM derived from RADARSAT-2 data, MDA acquired publicly-available 90 m Shuttle Topographic Radar Mission (SRTM) DEM data, and analysed it for comparison purposes. Slope and relative elevation layers were derived from the RADARSAT and SRTM DEMs using terrain analysis programs.

- Percent slope is the ratio of the increase in height per length expressed as a percentage.
- Relative elevation difference is a measure of relative height of individual pixels as related to their surrounding pixels. This is a useful characterisation of terrain that assists in identifying ridges and valleys and quantifying their relative height or depth.

3.2 Optical data review

3.2.1 Optical data selection

Optical satellite data was used for the visual and quantitative analysis of the impact of the mining disaster on the vegetation and land cover. The Marinduque Island area of study was covered by Landsat path 115/row 51.

Landsat data was selected because it is freely available, often has many dates of images for the same footprint, was in service during the time that the Marcopper disaster occurred, is of a high enough resolution for the study area, and now offers a free surface-reflectance processing. Landsat images are the only satellite data which fit all of these criteria for doing this study. Multispectral imagery from the three different Landsat satellites where used: Landsat 8, 7, and 5.

Since we were looking at each pixel over a number of years, it was important to have as few clouds as possible. This is because in a time series analysis, each pixel contributes to the layer statistics. Clouds are not relevant and so are masked out, but the masks are cumulative over the layer stack. Out of the hundreds of Landsat images that were searched, only four were cloud free enough and of good enough quality to use for the detailed investigations of this study: (1) November 13, 1996 — Landsat 5; (2) January 3, 2001 — Landsat 7; (3) February 13, 2007 — Landsat 5; and (4) August 10, 2014 — Landsat 8. In addition, over a dozen Landsat images acquired between 1993 and 2013 were used to conduct an automated multidate change analysis.

3.2.2 Optical data processing and evaluation methods

All four of the Landsat scenes used in this study were transformed for surface reflection by the USGS Earth Resources Observation an Science(EROS) Data Center (EDC). This was specified because this process makes the images more radiometrically calibrated and thus derived products such as NDVI are more accurate and comparable. The EDC also distributes an ancillary thematic dataset associated with each image called the CFMASK. This mask includes several categories used to mask unwanted features from the image including clouds, cloud shadows, water, and snow.

Several stages of processing of the imagery were required to create the products used for the analyses. These were:

- *Pre-processing:* The image data for each scene were layer stacked into 6-band images for comparison, and the scenes were cropped to a square frame tightly fitting only the island. Then the CFMASK was used to mask out cloud and cloud shadow.
- *NDVI:* Once the layer stacks were completed, each image was transformed using the NDVI. This transformation expresses features with high chlorophyll content with higher values, and is a standard transformation for measuring the presence and health of vegetation (Jensen 1996). Four NDVI's were produced, one for each scene. Water was removed during this process using the CFMASK.

  The NDVI results were then stacked into a 4-band layer in order of the dates of the imagery. A stack-standard deviation function was run on the layer stack in order to show areas of greatest change in vegetation presence. A threshold was applied such that greater than 10 standard deviations was considered change. A ruleset was applied to the NDVI layer stack to characterise the change in vegetation content at each pixel.
- *Persistent Change Monitoring (PCM™):* A persistent change is a shift in land cover which persists over time, such as new building construction, forest clearing, and other human-induced activity and requires the use of stacks of imagery to identify the change. PCM™ is designed to differentiate between persistent changes, which are more likely to be man-made, and transient changes by comparing several images of the same location over a period of several years. Transient environmental changes such as cloud cover, sun angle, seasonal vegetation, and agriculture are not flagged as real change.

- *Land Cover Classification:* The earliest and latest dates of imagery were selected for doing land cover classification. These dates were 13 November 1996 and 8 August 2014. Fortunately there is little difference in vegetative seasonality at this latitude of around 13 degrees for the different dates. However there was some difference in sun angle in the two images which created some consistency difficulties.

A supervised classification and regression tree (CART) based method was selected for this study. Training points were collected over all of Marinduque Island. The points were selected at random and assigned a value based on a 13-class classification scheme discussed in Section 4. The training points were then used to classify the Landsat image bands using a regression-tree classifier. The raw results were then refined by running despeckling algorithms and hand editing. Both dates were classified independently and were then input into a Summary function to create a change matrix. This matrix quantifies the 'from class/to class' change over the period of the study.

4 Results

This section presents the results of the preliminary remote sensing evaluation of three portions of Marinduque Island:

- The causeway at Calancan Bay.
- The Tapian and San Antonio pit areas.
- The Boac River drainage basin (including the Bol River).

4.1 Calancan Bay Tailings Causeway

The change over time in the vicinity of the Calancan Bay Tailings Causeway was assessed using optical imagery with two different approaches. The first approach involved a simple visual comparison of a time series of optical images. Although this is a relatively low-tech approach, it can be highly effective. Figure 2 is a screenshot of these results.

The upper left hand frame of Figure 2 side shows conditions in 1996, five years after discharge into the bay stopped. The other frames show the progression of vegetation and erosion of the causeway. The white cross-hair is at the same geographic coordinates in each of the images, and can be used to evaluate the change in the causeway's areal extent over time. The True Colour processing selected for this display will show features in very shallow water as pale blue, and the portions above water as either white or (if vegetated) green. Areas of clouds and cloud shadow were masked out, and are shown in black.

In the 18 year period covered by this sequence of images, the end of the causeway has retreated roughly 550 m; the causeway has narrowed, and new areas of sedimentation (spits) connect the causeway with Banot Island to the west, and also with the shoreline area in the southeast. These observations are consistent with reports from the USGS ground crew (The Futures Group International 2004) and other sources.

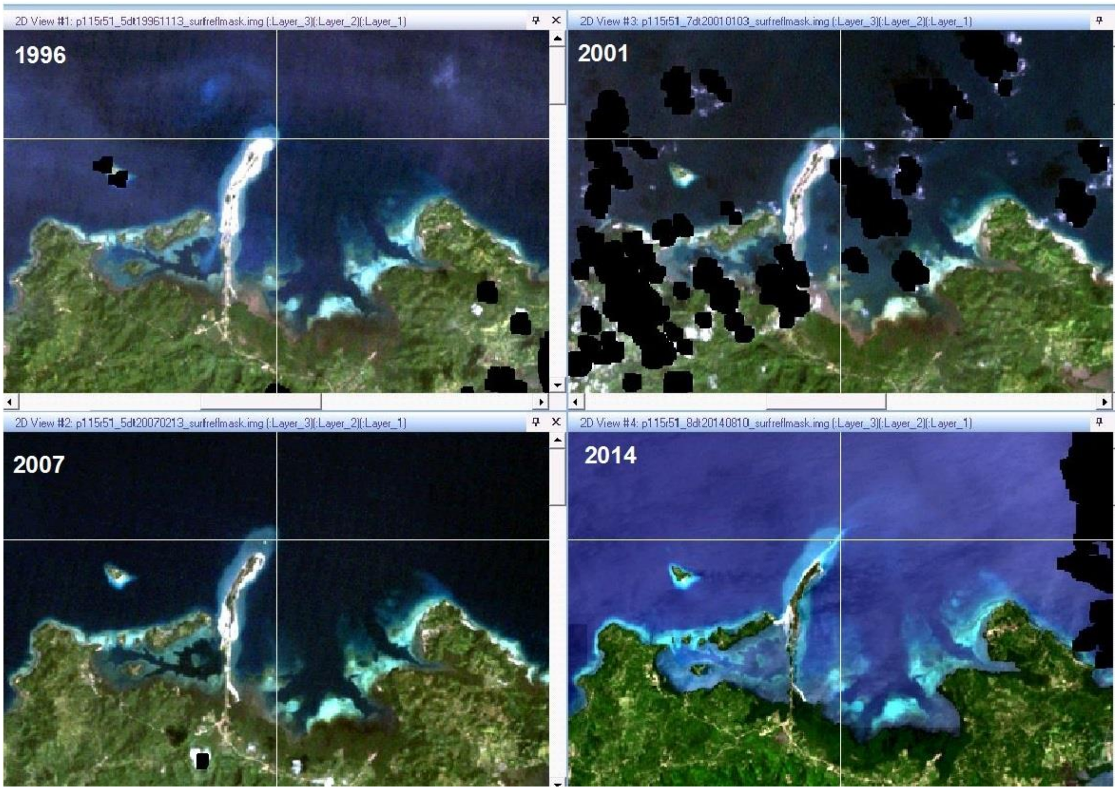


Figure 2 Time sequence of Landsat imagery of Calancan Bay, showing erosion of tailings causeway (Landsat 2014)

The second approach that was used to evaluate the causeway change was PCM™. In the PCM™ output shown in Figure 3, the different colours indicate the year that a change was considered to be permanent. The pixels indicating the year of change can be queried using a GIS system to determine the most-likely type of change based on the optical images' spectral properties. For example, the change in the centre of the causeway in 2001 is described as likely being due to a change from barren to vegetated, and the changes at the end of the causeway are described as likely being due to a change from land to water. The benefit of using this type of analysis is that areas and dates of change can be quickly identified, so that the analyst can then focus on evaluating the causes or potential results from real change and not be side tracked by false positives. This type of analysis may also identify gradual change that might be overlooked.

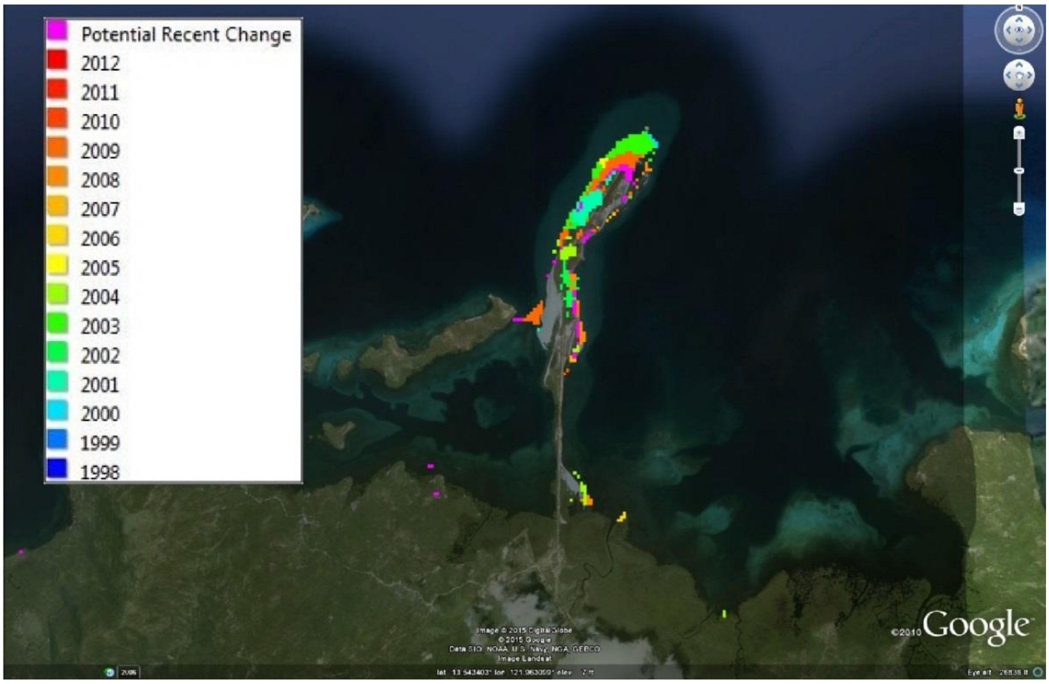
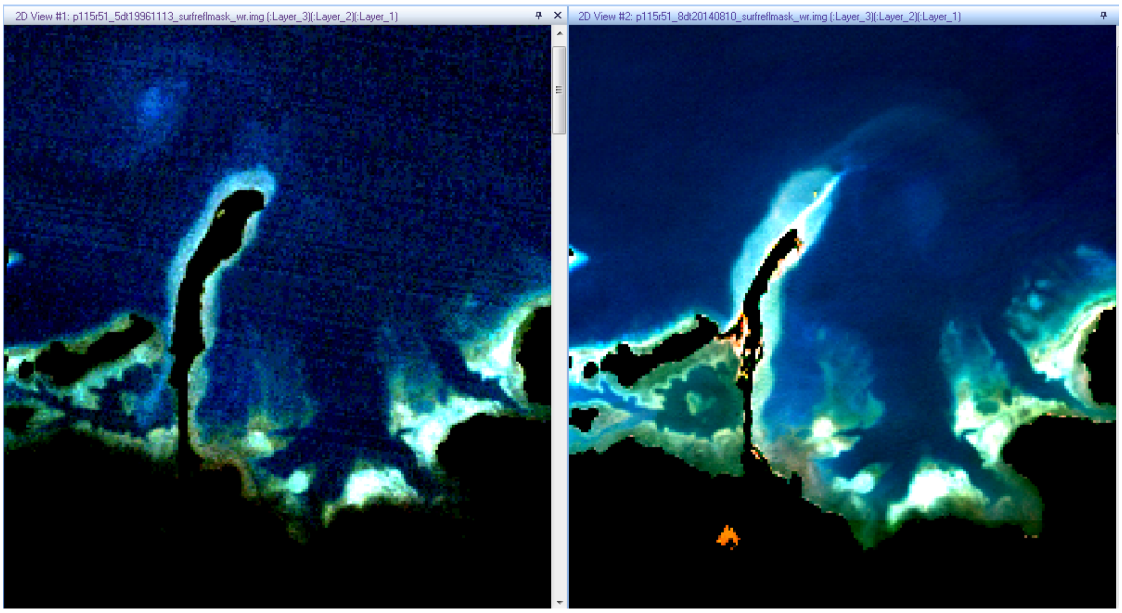


Figure 3 **MDA's PCM™ processing results for Calancan Bay. Background image is from GoogleEarth and was acquired in May, 2006 (GoogleEarth 2014)**

The PCM™ example in Figure 3 is derived from 30 m resolution Landsat data, but could also have been done using 5 m data (such as RapidEye) if sufficient historical imagery was in archives. The 5 m change products would detect smaller areas of change, and would more precisely show the changed area's location.

The optical imagery was also processed to show areas of turbidity and seabed topography (Figure 4). Here, every area that is above water is shown in black. In the colour version of this image, shallow features are shown in white, and slightly deeper areas are cyan. The purple and pink areas near shore are regions where some factor, such as sediment, is causing an unusual spectral response.



(a) (b)

Figure 4 **(a) Screenshot of Landsat 5 image from November 11, 1996; and (b) Landsat 8 image from August 10, 2014 processed to highlight underwater features (Landsat 2014)**

4.2 Tapian and San Antonio Pit areas

The Tapian and San Antonio Pit areas were evaluated using a combination of layers derived from optical and RADAR images. The derived optical products included detailed 30 m land cover from two different sensors and NDVI values from four dates. 10 m DEMs were derived from RADARSAT imagery, then used to develop a series of terrain analysis layers. The products were used in conjunction with each other to develop a preliminary assessment of conditions over time in the vicinity of the pit areas.

4.2.1 Land cover classification

A comparison of 30 m Landsat-derived land cover classifications for 1996 and 2014 in the vicinity of the pits is provided in Figure 5. This figure shows an increase in the size of the open pit lakes and an increase in forest, grass, and scrub vegetation within the footprint of the mine waste landforms. However, there is also a corresponding decrease in urban/human influenced areas as well as agricultural activity near the mines.

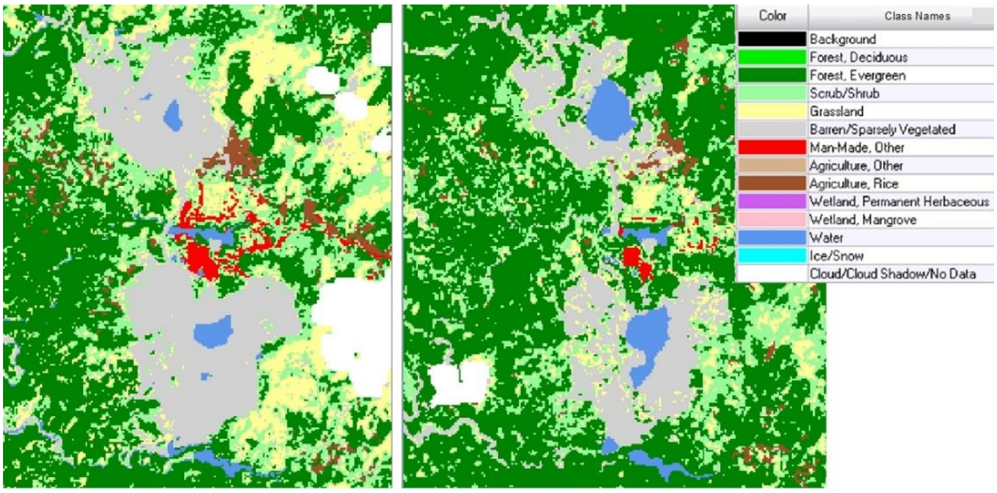


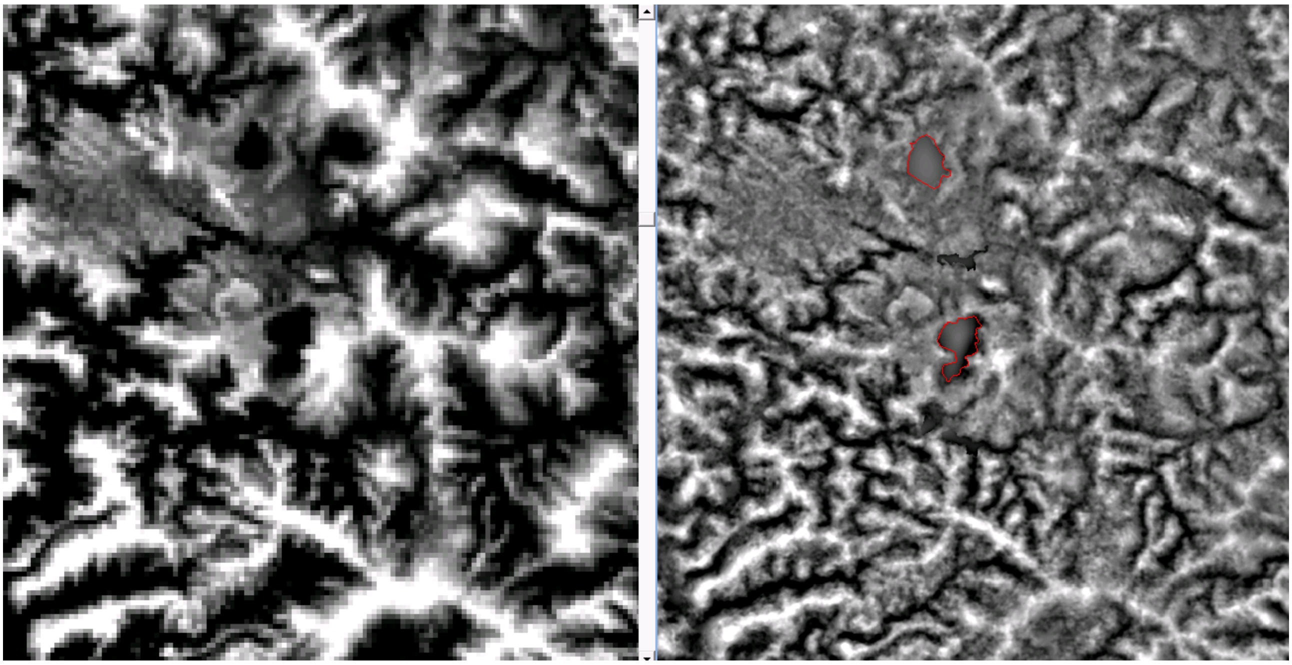
Figure 5 Marcopper mine area showing land cover change. The upper left panel contains the land cover results for 1996 and the lower left panel contains the results for 2014. Coconut plantations are included in the 'Forest, Evergreen' class

4.2.2 Terrain analysis

The areas with both barren soils and steep slopes are typically considered to be areas most at risk of excessive erosion or localised slope instability. Ideally, InSAR would be used to identify localised areas that may already be experiencing differential changes in elevation due to erosion. However, the available sources of historical SAR imagery do not provide enough suitable archival data to provide a meaningful InSAR interpretation. Therefore, a different approach has been used which combines land cover and terrain morphology analysis to evaluate areas that might be most at risk.

Terrain analysis involves characterising earth surface morphology from DEM data. Typical outputs often include slope, aspect, and max-min values; although more-complex analysis can also be enlightening. For example, relative elevation shown the layer shown here is used in localised geohazard assessments. The efficacy of a terrain analysis is often dependent on the resolution of the parent DEM. To illustrate this concept, we conducted our analysis using the 90 m resolution SRTM dataset and the 10 m resolution DEM generated by MDA.

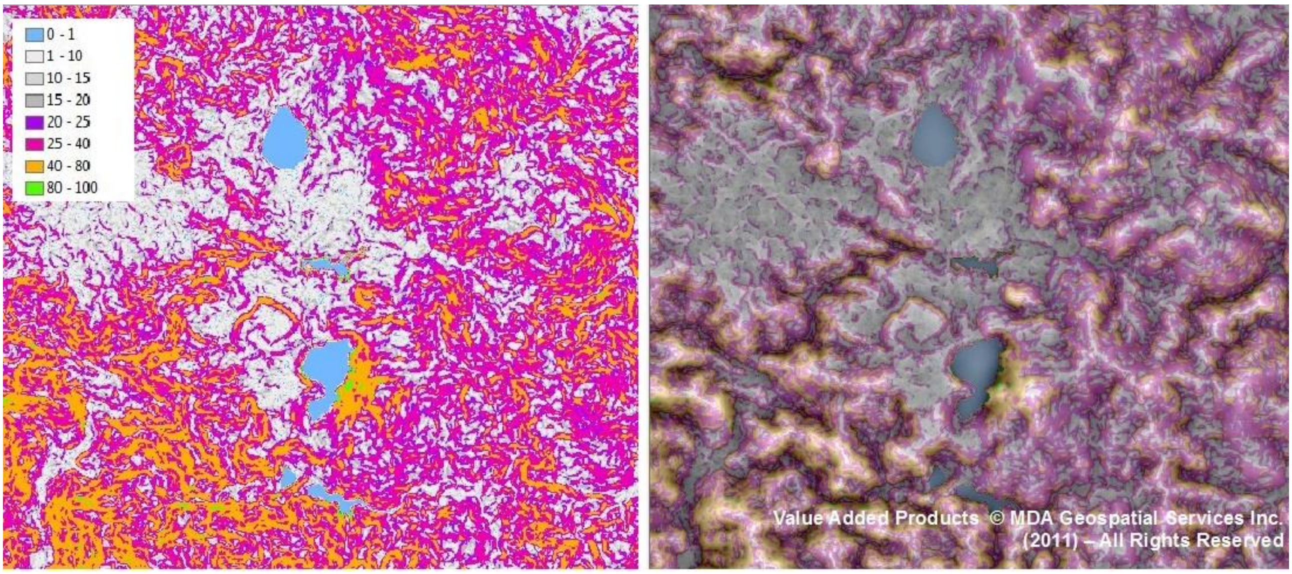
Figure 6 shows a comparison of the detail that is provided in a relative elevation layers for each of these data sets. The higher resolution DEM clearly shows details that could be missed if only the coarser resolution DEM had been used. For example, the relative elevation of the 10 m DEM shows that the area east of the Tapian pit has a much more complex morphology, including a series of E-W trending features, than is shown in the SRTM layer. Similarly, there is a relative low east of the San Antonio pit that the 10 m data shows is really the confluence of three small drainages — a detailed not shown by the 90 m SRTM data.



(a) (b)

Figure 6 (a) Relative elevation extracted from 90 m SRTM data; (b) the 10 m DEM shown in the vicinity of the Marcopper Mine. The brighter colours indicate the areas of highest relative elevation (source: MDA Geospatial Services Inc. 2011)

Figure 7 shows the slope angles (in percent) over the pit areas derived from the 10 m data set alone and also superimposed on relative elevation. The superposition shows that the steepest areas in this region tend to be on the side slopes of the valleys, with the exception of the steep eastern wall of the Tapian Pit.

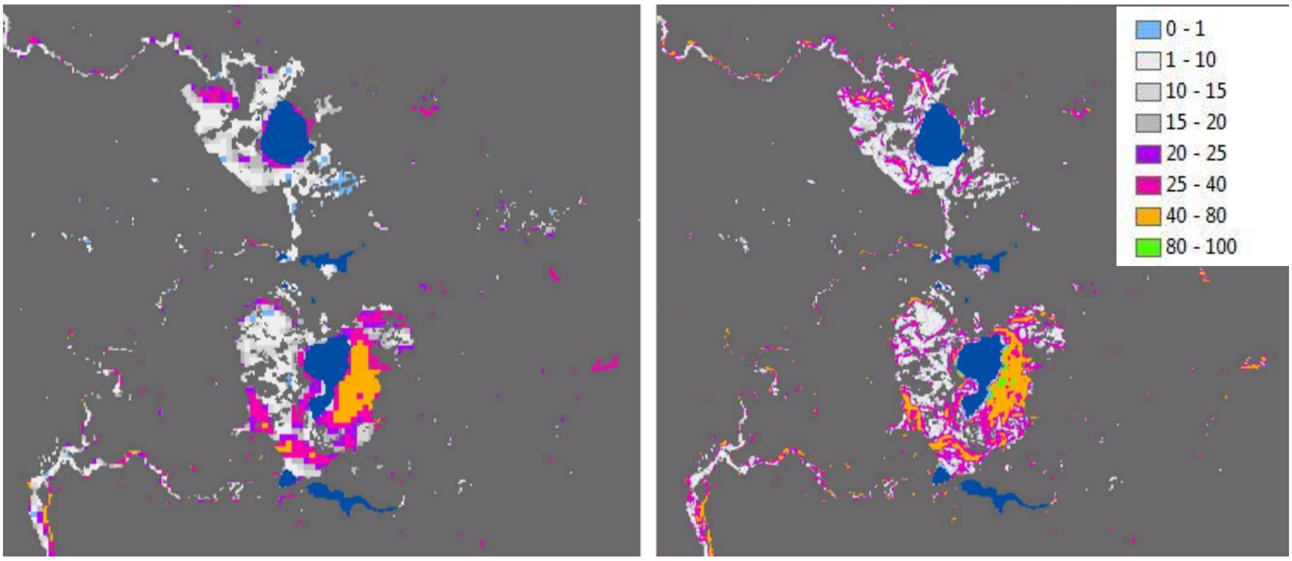


(a) (b)

Figure 7 (a) Slope angles calculated from the 10 m DEM. Areas covered by water are shown in blue. (b) Slope superimposed on relative elevation (source: MDA Geospatial Services Inc. 2011)

4.2.3 Integration of results

The regions that would be expected to be most at risk for sediment movement or slope instability would be those with steep slopes that are barren or adjacent to water bodies. These areas can be identified by combining land cover and slope information. A mask was created of all 2014 land cover types other than barren and water and was superimposed on the slopes derived from the two DEMs for this area (Figure 8).



(a) (b)

Figure 8 Slope in barren areas in the vicinity of the San Antonio and Tapian Pits. (a) Shows slope calculated from SRTM; and (b) shows slope derived from the 10 m DEM (source: MDA Geospatial Services Inc. 2011)

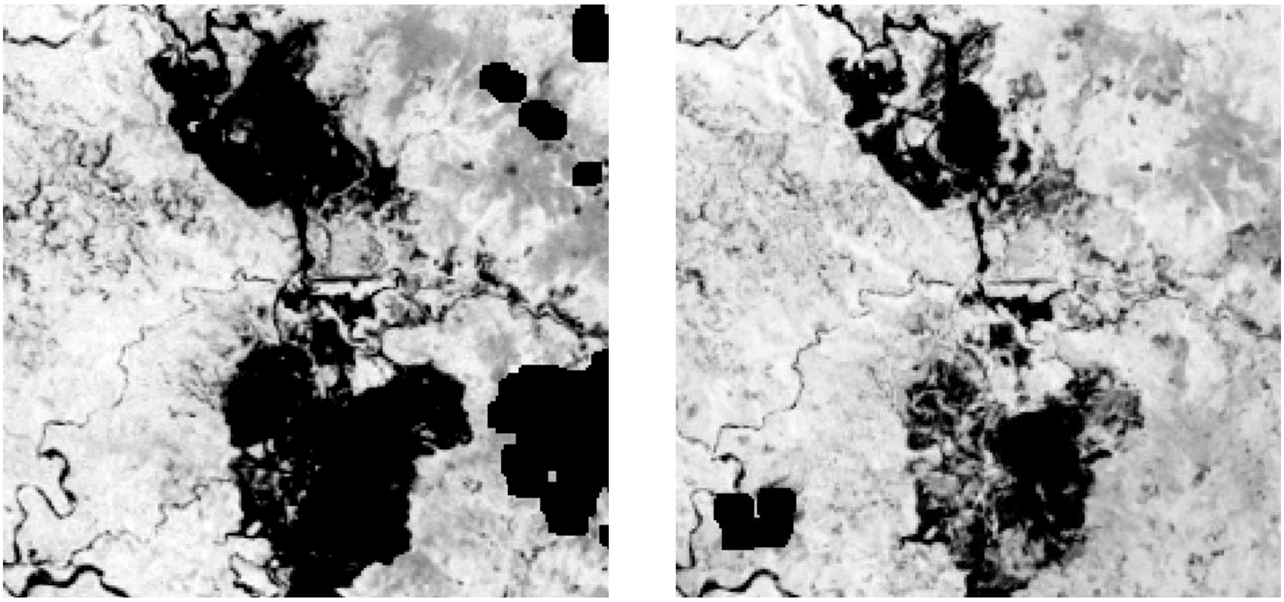
By focusing on the barren areas and slope, the areas that are particularly susceptible to instability and/or accelerated erosion are highlighted. This does not mean that the other areas should be ignored, but it can help prioritise monitoring resources. The value of using a higher-resolution DEM is also illustrated by Figure 8. The higher-resolution DEM picked up several areas in the western portion of the pits that would have been completely missed if only the 90 m DEM had been used. In addition, the higher resolution data shows much greater detail of the slope conditions on the eastern side. In the coloured version of this figure, areas of water are shown in bright blue, vegetated areas are masked and shown in grey, and the other colours represent the percent slope as shown by the legend.

4.3 Regional assessment

4.3.1 NDVI analysis

NDVI values derived from Landsat images acquired between 1996 and 2014 were compared to each other to evaluate the relative change in vegetation vigour throughout the region over time, with particular attention paid to the Boac and Mogpog River Basins.

The NDVI results are represented by grayscale layers. The brighter the pixel, the more green vegetation occurs at that location. In general, Marinduque has a high vegetation content for most of the island. There are certain areas where vegetation may have been impacted by human activity. If we focus in on the Marcopper mining areas, a substantial increase in the presence of vegetation can be seen (Figure 9). This layer is useful to compare vegetative content at each pixel from year to year and also to quantify the amount of vegetation for each date.



(a) (b)

Figure 9 Comparison of vegetative extent in the Marcopper mine area. (a) Contains the NDVI for the 1996 scene; (b) contains the NDVI results for the 2014 scene. Notice the increase in vegetative growth (lighter coloured areas) over the 18-year period

By stacking the NDVI results together, patterns emerge regarding the vegetation change history. We used two approaches to assist with understanding this change in vegetation vigour. The first was a stack-standard deviation (Figure 10). This layer demonstrates how the above NDVI layers can be used to quantify change in vegetative properties. The standard deviation output is a grayscale image where the greater the amount of vegetative change in the stack of NDVIs, the brighter the pixel value. This is useful to quickly locate areas of interest for potential reclamation.

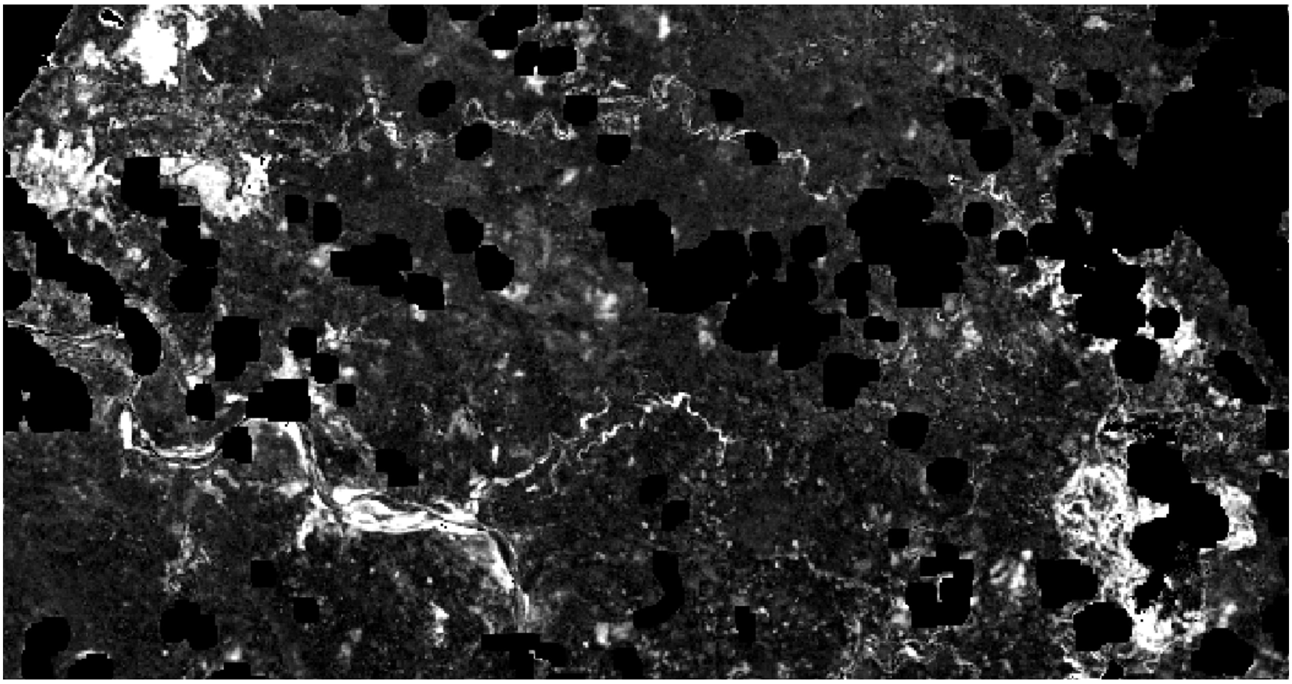


Figure 10 Stack-standard deviation layer showing change magnitude over four dates of imagery during the 18-year period. In the lower right, the Tapian Pit of the Marcopper Mine shows a large amount of change

A rule-based change characterisation was performed to further analyse the vegetative change in the study area. The inputs into the rule-based change characterisation model were the stack-standard deviation layer, the four-date NDVI stack, and the ruleset developed to show change over time (Figure 11). The standard deviation layer was used to determine significant versus insignificant change to create a change mask. Then the rules were applied to the NDVI stack variables within the change mask. The model then produced a nine-class layer (Figure 12), and provided information on the acreage that fell into each class.

	Acres	Color	Class
0	530008		Change not significant
1	966.973		Decreases consistently
2	3910.59		Decreases until 2007, then rises in 2014
3	875.569		Decreases until 2001, then rises in 2007, then decreases in 2014
4	992.994		Decreases until 2001, then rises in 2007, and again in 2014
5	1515.62		Increases until 2001, then decreases in 2007 and again in 2014
6	1164.46		Increases until 2007, then decreases in 2014
7	2483.93		Increases until 2001, then decreases in 2007, then increases in 2014
8	936.061		Increases consistently

Figure 11 Four-Date NDVI stack output information and legend. The acreage shown is for the entire island

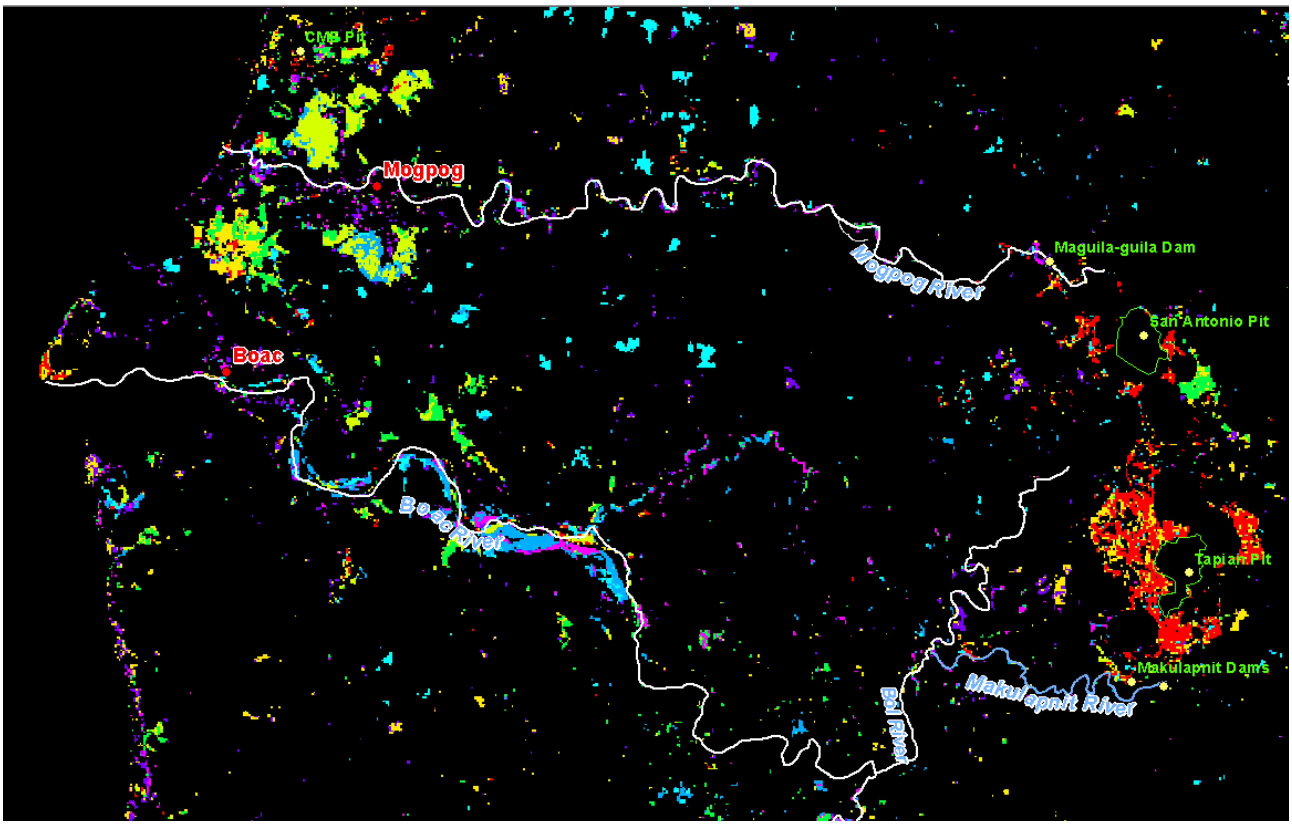


Figure 12 Results of the rule-based NDVI change characterisation. The rivers are shown in outlined in white. Areas of clouds and no significant change are shown in black

The rule based characterisation provides the change based on the NDVI value compared to the dates before and after it. A pixel value of 0 suggests there was not a significant amount of change and it is blacked out. Cloud areas are also blacked out. Pixels of class 1 (magenta) suggest that through time, the vegetative content of the pixel decreased year to year. This seems to occur mainly within waterways. This may be due to increased sediment deposit in the stream beds or pollution. Also in the stream beds there is a lot of increase and decrease (blues). This may be due to water level differences among the four dates. Class 8 (red) pixels increases continuously over the years. As expected, the Marcopper mine area (lower right of the scene) shows this increase as vegetation which has re-established in the disturbed mining areas. Based on the information in Table 4, we can tell that nearly 1,000 acres increased consistently over the entire island. It is also apparent that somewhere between 2001 and 2007 there was large scale vegetation removal as identified in classes 5 and 7 although these areas are closer to the towns of Mogpog and Boac and therefore do not appear to be mining related. These areas are represented in yellow and green in the layer. With an understanding of the history of the island and this layer, some further in depth analysis can be undertaken.

4.3.2 Land cover analysis

The regional land cover classification results were used to calculate the 'from class to class' change for the entire island. The results of this analysis showed that roughly 16% of the island changed between 1996 and 2014 (this number does not include the change due to clouds). This is considered a very high rate of change. Ignoring cloud effects, the largest transformations in land cover are related to forest, scrub/shrub, and grassland categories. This type of change is usually due to forest harvesting/replanting activities and accounts for over half of the change recorded on the island. Another notable change is that of bare soil to vegetated categories such as grass and scrub. There was a reduction in rice agriculture as well. Interestingly there was also a reduction in urban features.

5 Summary of results and recommendations

5.1 Summary of results

This study demonstrates the utility of satellite imagery for the quantification of change, even in in tropical locations such as Marinduque Island which presents several remote sensing challenges. The findings showed that a significant amount of change has occurred on the island. There are still barren areas in steep-sloped regions near the mine pits and tailings dams that could be vulnerable to ongoing erosion or localised instability.

Over the past 18 years, the mine tailing causeway in Calancan Bay has lost roughly 550 m in length from erosion by the sea. In the vicinity of the Marcopper mine pits and mine waste landforms there has been a gradual increase in vegetation cover as well as an increase in the size of the pit lakes.

5.2 Recommendations

This results of this study suggests that satellite monitoring should continue into the future for this island. Future characterisation could be improved by:

- Analysing 5 m or better resolution optical imagery to better assess details of affected areas.
- Use of InSAR to monitor ground movement (e.g. settling, erosion, other geotechnical risks) across the impacted areas.

Additional multi-date studies could be undertaken using Landsat images, an approach that would mitigate the effects of clouds. Use of multi-date analysis techniques would allow each pixel to have enough coverage so that a standard deviation for each pixel in a stack of all the images would still be meaningful. In addition, a series of Landsat and other imagery could be processed to evaluate changes in underwater sedimentation near the shoreline over time. In addition, a 5 m PCM™ study could show detailed changes near pits and other areas over time.

The newly-launched WorldView-3 (WV-3) satellite data provides high resolution data from the same spectral bands as the ASTER sensor that is used to map minerals at 15 m and 30 m resolution. Research is needed to see if WV-3 imagery can be used to identify pockets of contaminated sediments and acid mine drainage.

In the last decade, INSAR analysis procedures have been validated and used operationally with different types of space borne SAR data in many regions of the world. InSAR can provide valuable understanding of deformation patterns over both active and former mine sites. Suggested possible considerations for future monitoring are:

- Programming higher resolution modes to establish baselines.
- Appropriate InSAR survey design and additional data over a consistent time series, to provide a wider spatial analysis over mine operations.
- Application of advanced InSAR monitoring algorithms using natural or artificial hard targets. It could be possible to more precisely measure movement of those features showing deformation. Research using future L-Band SAR sensors could provide additional support to monitor deformation motion for mines located within tropical regions of the world.

Finally, the results of any remote sensing study should always be integrated with ground truth where possible.

Acknowledgement

SAR data was provided by the European Space Agency, Canadian Space Agency and MDA. We would like to acknowledge the support of the Australian Centre of Geomechanics, MDA Geospatial Services Inc. and MDA Information Systems LLC for the support for this work and permission to publish the materials.

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