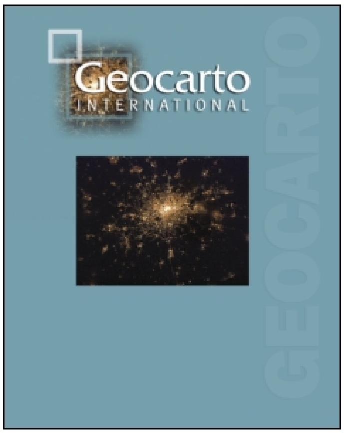

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Monitoring the Environmental Impact of Mining in Remote Locations through Remotely Sensed Data

David Paull [a]; Glenn Banks [a]; Chris Ballard [b]; David Gillieson [c]
[a] School of Physical, Environmental and Mathematical Sciences, University College, The University of New South Wales, Canberra, Australia [b] Division of Pacific and Asian History, Research School of Pacific and Asian Studies, The Australian National University, Canberra, Australia [c] School of Tropical Environmental Studies and Geography, James Cook University, Cairns, Queensland, Australia

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Monitoring the Environmental Impact of Mining in Remote Locations through Remotely Sensed Data

David Paull and **Glenn Banks**
School of Physical, Environmental and Mathematical Sciences
University College, The University of New South Wales
Northcott Drive, Canberra ACT 2600, Australia
E-mail: David.Paull@adfa.edu.au
Glenn.Banks@adfa.edu.au

Chris Ballard
Division of Pacific and Asian History, Research School of Pacific and Asian Studies
The Australian National University
Canberra ACT 0200, Australia
E-mail: Chris.Ballard@anu.edu.au

David Gillieson
School of Tropical Environmental Studies and Geography, James Cook University, PO Box 6811 Cairns, Queensland 4870, Australia
E-mail: David.Gillieson@jcu.edu.au

Abstract

Mining is an integral part of the development of many countries in the Asia-Pacific region and is associated with adverse environmental and social impacts. The monitoring of mining in remote locations is problematic due to difficulties of access. Satellite remote sensing is able to provide information on landscape transformation in a cost-effective way around large-scale mines. The PT Freeport Indonesia mine in Papua (Indonesia) is the world's largest copper-gold mine and previous studies have documented a range of impacts. A multi-temporal analysis of Landsat 5 imagery of the Freeport area was undertaken for the years between 1988 and 2004. Anthropogenic land cover changes were quantified by screen digitising polygons from three false colour composite images over this period to determine the area of forested land that had been cleared and the area that had been affected by mine-derived sediment transported by the Ajkwa River system. The results show that both settlement and sediment had radically altered land cover and together had led to a sixfold increase in the area of ultra-diverse lowland tropical rainforest cleared in the study area. The study highlights the utility of this method to monitor elements of the impact of large-scale mining and other extensive forms of resource exploitation such as deforestation in developing countries.

Introduction

The extraction and exploitation of natural resources in the Asia-Pacific region is increasingly intensive and contested due to a combination of factors, including economic growth, population growth and resource depletion. Pressure is increasing on freshwater resources (Shah *et al*., 2003), agricultural land (Hill, 2002), forests (Dauvergne, 2001), fisheries (Hviding and Baines, 1996) and minerals (Ballard and Banks, 2003). These resources are employed as inputs into economic development within the region, and the extraction of the resource itself is commonly regarded as a stimulus for local and national development. The region is, in this sense, an example of a resource frontier, similar in nature and extent to other resource-rich parts of the developing world.

The extraction of natural resources has generated a range of resource-specific impacts. Of these, the effects of large scale mining have provided some of the most spectacular environmental disasters in the region, with mining operations such as Ok Tedi (Banks and Ballard, 1997), Marinduque (David, 2002) and Freeport (Leith, 2003) becoming emblematic of the excesses of resource-driven development in the region. There are a number of reasons that contribute to the significant environmental impacts of these resource developments: they generally occur in relatively remote locations (leading to an attitude of 'out of sight, out of mind'); governments in these countries, in a push for

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development, tend to enforce lower environmental standards than in the developed world; and, for both of these reasons, there is little external scrutiny of the operations. Local communities and environments around these operations tend, therefore, to be the losers, but they are generally unseen casualties in a broader national development discourse.

There has been a growing interest in both mining and forestry in the Asia-Pacific region amongst international NGOs, acting as 'watchdogs' of state and corporate behaviour. The Mineral Policy Institute (based in Australia), the Mineral Policy Centre and the Tropical Rainforest Coalition (both based in the United States) are just three examples of such organisations; they are typically chronically under-funded and have limited ability to undertake direct monitoring of these resource extraction projects by themselves. In these situations the NGOs rely on a variety of generally local sources for information, but are rarely able to provide a comprehensive external overview of the changes that the mines are effecting.

In this situation, remotely sensed data are able to provide information on changes in local environments in a cost-effective way. This strategy parallels studies that have used remote sensing to examine change in agricultural practices (Haack *et al.*, 1998) and fire and land use change (Jones, 1998) in physically remote and/or politically hostile environments. In the case of the environmental impact of mining, such data can potentially help in assessing changes in land cover, the extent of the physical impact of mining operations (infrastructure, mining pits, sedimentation, etc), as well as the effects of migration and settlement dynamics, particularly when used in conjunction with other forms or sources of data. Imagery, and particularly Landsat, is now widely available and relatively cheap or even free in some cases (see, for example, NASA, n.d.), and access to such imagery does not require the permission of governments or companies.

The aim of this paper is to use the case of the Freeport copper-gold mine in Papua (Indonesia) to highlight the utility of remotely sensed data for monitoring aspects of the impact of large-scale mines in the region. The remainder of the paper is divided into four substantive sections: a brief review of the monitoring of the environmental impacts of the large mines in Asia-Pacific and the use of remotely sensed data in the environmental management of mine operations; some background on the PT Freeport Indonesia (PTFI) project being used here as a case study; a review of data and methods used in the analysis, based primarily on three Landsat 5 images of the Freeport concession area; and a discussion of the types of land cover changes apparent from the multi-temporal analysis. We conclude by returning to the potential and the constraints of monitoring large-scale mines in this manner.

Environmental Monitoring and Remote Sensing in the Mining Industry

Until the 1980s, there was little emphasis placed on the environmental impact, or management of the environmental effects, of mining operations in the Asia-Pacific region. There were, for example, no environmental impact assessments prior to construction in the late 1960s at either the Bougainville Copper Ltd (BCL) mine in Papua New Guinea or the Freeport mine in Indonesia. The situation is much improved now: most of the large-scale mines operate extensive environmental monitoring programmes, but public access to the data generated is usually tightly controlled. Due to this restriction on access to results, combined with the remote locations of many of the large mines and, in some cases, corporate or government controls on visiting mining areas (as is the case with PTFI's operations), there has been little independent long-term monitoring of any of the large-scale mine operations in the region.

The mining industry has been an extensive user of remotely-sensed data and GIS technologies for many years, but the focus has primarily been on the utility of the technology to assist with mineral exploration and modelling (see Akhavi *et al*., 2001 and Liu *et al*., 2000 for two recent examples of this application). More recently, remote sensing and GIS have been incorporated into the environmental management regimes of mining operations and areas affected by mining operations, predominately in the more developed economies (Lamb, 2000). The European MINEO project (Marsh, 2000) and similar projects in the USA (see, for example, Rockwell and McDougal, 2002) have employed remotely sensed hyperspectral data to assist with the monitoring and rehabilitation of mine waste areas. In such contexts the applications tend to be highly specialized, utilising high resolution hyperspectral data for the identification of the metal component of mine waste areas (Flemming and Marsh, 2002), mapping the distribution of acid-generating components in waste material (Ferrier, 2002), and evaluating the impacts of mine waste on the vitality of different vegetation communities (Fischer and Brunn, 2002). PTFI utilise remote sensing as part of their environmental monitoring but the data generated are not disseminated beyond highly specialized academic papers (see, for example, Ticehurst *et al*., 2001).

In the case study that follows, a relatively simple and straightforward methodology is proposed that allows for an overview of the environmental and social impact of large-scale mines in remote regions, based on a multi-temporal approach (see Rigina, 2002 for a broadly analogous example). In this sense the application is closer in its approach to work done on the remote sensing of forest change in the tropics (see for example Curran *et al.*, 2004 and Stibig and Malingreau, 2003) than it is to the more specialized applications described above for mining areas.

The Freeport Mine

The PTFI mine in Papua Province in Indonesia (Figure 1) is one of the largest mining operations in the world. It is a mine of superlatives: it has the largest reserves of copper and the second largest of gold of any project in the world. It was the largest gold producer in the world in 2003 (despite being primarily a copper mine) and is the lowest cost copper producer of any of the large mines (Freeport McMoRan, 2004a). The mine itself is located at over 4300 m within spectacular limestone country, adjacent to the last remaining glaciers on the island of New Guinea. The PTFI Contract of Work (CoW) operating area extends 80 km from the Grasberg pit at 4300 m down to sea-level. Rainfall in the area averages over 3000 mm/annum in the lowland areas and up to 5000 mm/annum in the highlands. The terrain and rainfall together create high-energy fluvial systems in the mountain sections and an extensive floodplain with meandering rivers in the lowlands. The extensive elevation range encompasses three broad vegetation zones (alpine, montane, and lowland, the latter incorporating rainforests, mangrove and coastal environments) with the general area described as having a high level of endemism and one of the highest rates of biodiversity in the Southeast Asia region (Leith, 2003).

The mine's history dates back to 1936, when a Dutch geologist attached to a mountaineering expedition noted the presence of a large mineralized ore body (the Ertsberg deposit) at about 4000 m, close to the summit of the Carstensz Range (Dozy *et al*., 1939). His report was stumbled upon in 1959

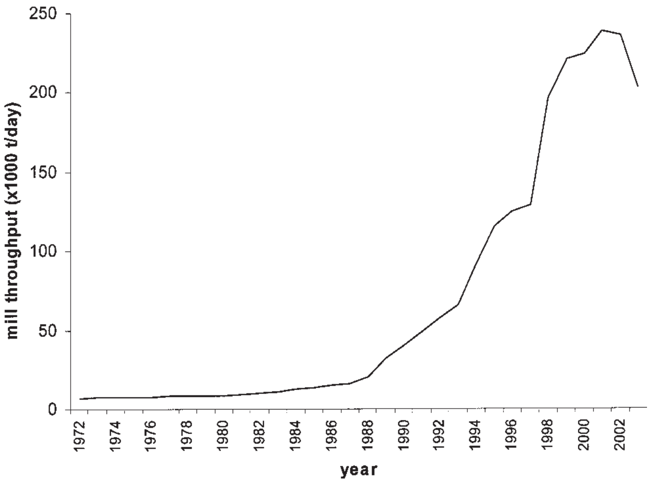

Figure 2 Freeport's daily mill throughput, 1972-2003. Sources: Mealey (1996), Freeport McMoRan (2002, 2004a). The decline in throughput in 2003 was due to a large landslide within the Grasberg open pit, which forced a temporary suspension of operations (Freeport McMoRan, 2004a).

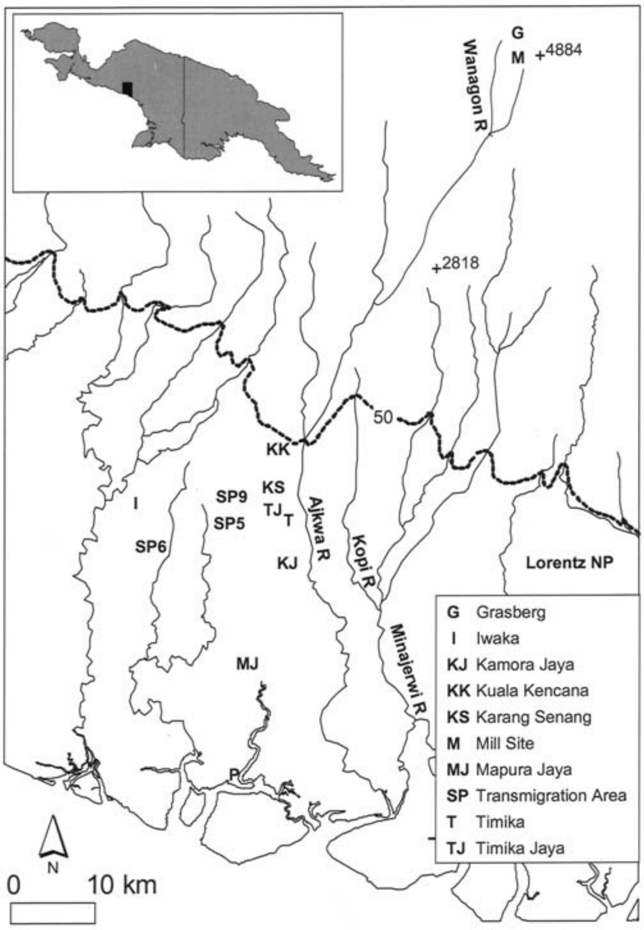

Figure 1 The Timika region showing its location and the major physiographic and cultural features referred to in the text. The 50 m contour illustrates the approximate divide between lowlands and highlands.

Figure 3 Photographs of the upper catchment of the Ajkwa River and downstream at the Ajkwa Deposition Area, 1997 (G. Banks).

by a geologist working for Freeport Sulphur, an American company primarily concerned with extracting sulphur from deposits in the Gulf of Mexico. In 1960 this geologist, Forbes Wilson, led an expedition to the deposit and within seven years Freeport had secured a CoW from the newly installed Suharto government in Indonesia. Construction began immediately and production commenced in 1972 (Wilson, 1981).

Up until 1988 Freeport remained a relatively small-scale operation, in a remote corner of a remote province of Indonesia. Exploration in 1988 at the nearby Grasberg deposit revealed the presence of what is currently the largest known deposit of copper and gold on the planet, and this ore-body was quickly incorporated into the mine operation (Mealey, 1996). The mine expanded rapidly, as demonstrated by the mill throughput data shown below (Figure 2). Production at Freeport in 2003 was 6.9 x 10^5 t of copper and 3.16 x 10^6 ounces of gold contained in concentrate. At this stage mine closure is anticipated for approximately 2041 (Freeport McMoRan, 2004a).

There are two Papuan language communities indigenous to the CoW area. The highland Amungme people are shifting cultivators with an agricultural system based around sweet potato, pandanus and pig production. They are closely related to the much larger central highland groups to the north of the main range. An estimated 800 Amungme were living in settlements in the valleys adjacent to the mine when construction began, and a survey in 1997 enumerated almost 4300 Amungme within the CoW area (UABS, 1998a). In the lowlands, the CoW area extends over territory that was previously the domain of the eastern Kamoro people. Kamoro were, and to a large extent still are, coastal and riverine dwellers with a subsistence system based on fish and sago (Harple, 2000). An estimated 950 Kamoro were resident within the CoW area in 1967, and this number had increased to over 8000 by 1997 (UABS, 1998b).

Since the mine development, and particularly in the period since 1988, there has been significant in-migration to the CoW area. The migrants include official government-sponsored transmigrants, mine employees and their families, members of the Kamoro and Amungme or related tribal groups from outside the CoW area, together with so-called ‘spontaneous migrants’ from other parts of Papua and Indonesia. Precise population figures for the various types of migrants are difficult to determine but the estimated total population within the CoW area has increased from 3000 in 1967 to more than 120 000 by 2002 (Ballard, 2002). This figure is significant, given that the entire population of the province is currently estimated to be only slightly more than 2 million. The effect of a migration has been a growth in settlement and access to this formerly remote hinterland. The Indonesian government has identified Timika, the town that has sprung up to service the mining and other subsequent developments, as a hub for regional development. From the 1960s, Timika has expanded from a way-station along the road from the mine to the coastal port of Amamapare, and has recorded the highest rate of growth of any urban community in Indonesia. The government is currently considering the creation of an entirely new province with Timika as its capital (Pickell and Muller, 2003).

Two sets of issues have dominated the debates concerning the impact of the mine on the local communities and environment. First, the relationship between Freeport and the indigenous communities has been problematic since the start of the mine. In large part this is due to the presence of a substantial contingent of Indonesian military forces within the CoW area, ostensibly to provide protection to the mine from local unrest. In one critical incident the military were involved in the murder and torture of Amungme in the CoW area in the highlands (ACFOA, 1995). This reflects a broader pattern that continues to the present day (Leith, 2003).

Second, little attention was given to the environmental impact of the mine prior to 1988. PTFI established an environmental laboratory in 1994 close to Timika airport. The Indonesian government has taken a much more active interest in the environmental aspects of the mine in the last decade, approving the first environmental impact assessment (or AMDAL in the Indonesian regulatory context) in 1995. A subsequent AMDAL to approve the mill expansion to 300 000 t/day was approved in 1997, and the mine operation was reviewed critically by the Indonesian Environmental Impact Management Agency (BAPEDAL) in 1999 (Leith, 2003). PTFI have consistently stated that they comply in all material respects with Indonesian law in terms of their operation and this has never been challenged by the government. Since 1996 PTFI have also commissioned and published two Environmental Audits of their operation (Dames and Moore, 1996; Montgomery Watson, 1999). These audits have again supported PTFI’s compliance with Indonesian law, although both raised some concerns about the scale and nature of the impacts. Leith (2003) also noted concerns over the independence and subsequent selective use by PTFI of these audits.

The environmental impacts of the PTFl operation are similar in nature to many other mines in the region, and revolve around management of the waste generated by the mining activities. This waste takes one of two primary forms: overburden or waste rock, and tailings. The former is material that is moved to access the metal bearing ore, and the Freeport operation currently moves approximately 500 000 t/d of overburden (Moffett and Adkerson, 2004) which is stored in a stable waste dump in the Wanogong River, in the headwaters of the Ajkwa catchment. Tailings are the finely ground residue of the milling and extraction process and at Freeport typically make up 97% of the ore that is processed (*i.e.* only the 3% copper and gold in the ore that enters the mill complex is extracted). A recent report published by the company provides a description of the tailings disposal system, noting that the company “uses the Ajkwa River system for tailings transport to a designated area in the lowlands and coastal zone, called the Modified Ajkwa Deposition Area (ModADA) which is an engineered, managed system for the deposition and control of tailings” (Freeport McMoRan, 2004b:4). The report notes that the ModADA currently covers 14 600 ha (or 146 km^2) of the Ajkwa Floodplain. This relatively benign statement conceals a dramatic sequence of physically extensive changes to the landscape, resource base and ecology of the floodplain area (Figure 3).

The analysis of the imagery contained below focuses on two major processes of landscape and land use change comprising impact of the tailings deposition area, and the less visually dramatic but arguably more insidious growth of the settlement area within and adjoining the CoW area.

Methodology

Image Analysis

Three Landsat 5 images were acquired for the purpose of monitoring land cover change in the Timika region (Figure 1). The images were captured from Path 103 / Row 63 on 27 May 1988, 27 December 1996 and 20 March 2004, providing snapshots of the region at approximately eight year intervals. Landsat 7 imagery for the 2004 scene was not used because data after 14 July 2003 were affected by the Scan Line Correction being turned off. Also, using images that were all captured by Landsat 5 had radiometric advantages in terms of image calibration. The centre of the three scenes was 4º30'S 136º55'E and the X/Y span was 75 km x 108 km. Following radiometric correction, the 1996 image was precision geocoded (level 9) by the Australian Centre for Remote Sensing (ACRES) using the cubic convolution re-sampling kernel to provide location precision of around 100 m. The 1988 and 2004 images were subsequently rectified using control points obtained from the 1996 image (*i.e.* image to image rectification), with the 1988 image being processed by Geoimage Australia and the 2004 image by the first author. The map projection was UTM (Zone SB53) and the earth ellipsoid was AGD66.

A common problem with satellite imagery from this tropical region is the presence of cloud. The three images each had some cloud cover but, after viewing all relevant Landsat scenes from the ACRES digital data catalogue, those selected were considered to be the best available for the desired timeframes. A certain amount of cloud cover, therefore, had to be accepted but in each case it did not obscure the main areas of interest, which were in the vicinity of Timika and the tailings deposition area.

To quantify human-induced land cover changes, polygons were manually screen digitised over each of the three images using ArcView GIS version 3.3, then area calculations were made for 1) the forested land that had been cleared (with or without settlements) and 2) the area affected within the ModADA. False colour composite displays (bands 5, 4 and 1) were used to enhance contrast between the major land cover types, with undisturbed forest appearing dark green, cleared and settled land appearing light green and red, and water and sediment in the ModADA appearing blue and pink (Figure 4). This methodology was chosen in preference to an image classification approach (either supervised of unsupervised) because our objective was to delineate only anthropogenic features and not other spatial phenomena such as naturally occurring sediment deposits in rivers. At the outset of the image analysis, supervised and unsupervised classifications had been made; however, satisfactory results were not obtained due to 1) the inability to distinguish human from natural changes, and 2) the huge variety of anthropogenic changes, including different stages of clearance and regrowth, different forms of infrastructure and different settlement forms. Horning (2004), writing for the American Museum of Natural History, appraised the benefits of conducting manual classification under the title of *Justification for Using Photo Interpretation Methods to Interpret Satellite Imagery*. Therein he concluded that the subjectivity of this approach is in fact its strength because "the human brain is still better at classifying the vast array of landscape features than a computer algorithm. The downside is that this approach is more susceptible to operator fatigue and bias than automated methods, and it tends to be slower in complex or large areas." To reduce the influence of bias upon our classification, the image interpreter (DP) worked closely with field researchers throughout the project so that we could have the greatest confidence in our classification accuracy. Two of the authors (GB and CB) spent a combined total of 12 months in the field area over the period 1997-1999, working closely with Kamoro and Amungme communities indigenous to the CoW area. They both travelled extensively through the area of interest and become familiar with the nature of changes in the physical and social landscape over this period. This fieldwork and the resulting reports (UABS 1998a, 1998b) allowed for a more refined interpretation of the changes evident in the imagery.

The analysis was restricted to the lowland below the 50 m contour and did not include the highlands or offshore areas. It should be noted, however, that both of these zones also experienced change during the survey period. In the highlands, this included significant areas of mine infrastructure, towns and the growth of indigenous (Amungme) settlements. In the case of offshore impacts, Leith (2003:168) noted a report that utilised Landsat 7 ETM imagery and found that up to 840 km of nearshore environment was "polluted" by tailings in 2000.

Results

Landscape Transformation Processes

Forman (1995) described five fundamental landscape transformation processes, being perforation, dissection, fragmentation, shrinkage and attrition. Of these, the major processes visible in the Timika Landsat series are dissection and perforation, which are the most frequent ways of commencing land cover change (Forman, 1995). Dissection was caused by a major road running for a point-to-point distance of approximately 80 km between the mine site and mill in the north and port site in the south, from where ore is shipped (Figure 4). Perforation is evident in the 1988 image with the cleared and settled areas at Timika, Timika Jaya, Karang Senang, Mapuru Jaya and Kamora Jaya, and it increased in the subsequent scenes when additional settlements appeared (notably Kuala Kencana, SP5, SP6 and SP9) and the original Ajkwa Deposition Area (ADA) grew. Lowland rainforest constituted the landscape matrix in all three scenes and thus the processes of fragmentation, attrition and shrinkage are not as evident as perforation and dissection, although some minor examples can be found, for instance where remnant patches of forest were left behind within the cleared and settled areas. Likewise, one small patch of remnant forest (approximately 125 ha) that was isolated within the ADA in 1996 disappeared completely through attrition by 2004.

Sediment and fluvial changes in the Ajkwa Deposition Area

In 1988 the ADA covered approximately 16 km^2 (Table 1). Although we did not view images prior to that year, a comparison with neighbouring watercourses supports our assumption that the substantial disturbance to the Ajkwa River immediately east of Timika was anthropogenic in origin and obviously related to the deposition of mine tailings in the Ajkwa River headwaters. In 1988 the average daily input to the river from the mill was approximately 19 400 t (20 000 t/day into the mill, less 3% copper and gold extracted) (Figure 2). By way of comparison, Leith (2003) noted that the natural average sediment carrying capacity of the Ajkwa River was 15 000-20 000 t/day. Between 1988 and 1996 the ADA increased 4.6 times in area to approximately 73 km^2, mainly through widening rather than lengthening. This reflects a six-fold increase between 1988 and 1996 to the average throughput from the mill to 125 000 t/day (Figure 2). Mealey (1996) pointed out that a violent storm contributed to the fluvial changes in 1990, when it washed substantial vegetation debris into the Ajkwa River and blocked its channel. As a consequence, sediment-laden water overtopped the banks and sheet flow spread eastwards through the forest to finally reach the Kopi River, which is part of the Minajerwi watershed to the east of the CoW area. We are not aware of any other rivers in the study area that showed a similar response to this storm, and hence the increased sediment load of the Ajkwa River was clearly a major factor in the dramatic fluvial transformation seen in the Landsat series in Figure 4.

Due to these disturbances to the Ajkwa River system, braiding or ‘anastomosing’ of the channels within the ADA had become very prominent by 1996 and levees had been constructed to the east, west and south by Freeport in an attempt to stop excess sediment from reaching Timika and the Kopi River. The cost to Freeport of these levees was reported by Mealey (1996) to be US$25 million to initiate and US$12 million *per annum* to maintain. The old Ajkwa River channel to the south of the ADA had ceased to flow by 1996 and was drying out (Mealey, 1996), and this can be seen in the 1996 and 2004 images. By 2004, the now-renamed Modified Ajkwa Deposition Area (ModADA) had grown to approximately 166 km^2 as a result of substantial lengthening caused by sediment transport southwards from the levee and outlet weir indicated on the Freeport Project Area Map (Freeport McMoRan, 1997) and visible in the southern part of the ADA in the 1996 image. The average sediment contribution to the river system from the tailings in 2004 was approximately 195 000 t/day (Figure 2). Anastomosing of the streams within the Deposition Zone was highly pronounced in the 2004 scene.

Vegetation loss within the deposition area is directly related to the build-up of sediment (Figure 3). In places the constructed levees are approaching 15 m in height and are responsible for the obviously delineated nature of most of the ADA and ModADA. The vegetation has been smothered by sediment (tailings) which, while also containing elevated levels of copper and some other heavy metals, was primarily a physical rather than chemical process.

Clearing and settlement

The area of cleared and settled land in the 1988 scene was approximately 44 km^2 or 2.8 times greater than the land area affected by the ADA. Although clearing and settlement progressed at a slower rate than enlargement of the ADA it had, nevertheless, reached 158 km^2 in 1996. This trend was also apparent in the 2004 image, by which time approximately 203 km^2 of the Timika region had been cleared and settled. The clearing mirrors the growth of the population within the CoW area, which increased from approximately 50 000 in 1990 to 120 000 in 2002 (Ballard, 2002). The bulk of this population is now resident in the lowlands, at a range of locations that can be identified in the imagery. Most of the mine management and their families reside in Kuala Kencana, with a distinctive circular road pattern. The transmigration areas (SP 1-11) are large geometric areas that initially give a strong signature (SP 5 in the 1996 image, for example) and subsequently become incorporated into a mosaic of further clearance, settlement and regrowth in later scenes. The earliest transmigrants and the bulk of spontaneous migrants live in Timika and its immediate surrounds, including both the peri-urban settlements of Kamoro Jaya, Karang Senang and Timika Jaya and the settlements along the corridor leading down to the river port at Mapuru Jaya. Iwaka, a refurbished Kamoro settlement, presents a distinctive linear feature. In the 2004 image, one of the worrying developments is the large settlement clearance to the east of the ModADA. This potentially opens up the area east to the Lorentz World Heritage-listed National Park boundary for clearance and settlement, and impinges on the Park itself through increased poaching of wildlife and collection of forest products.

Several interesting and identifiable features appeared during the survey period, for example the construction of

Table 1 Summary of the area affected by the Ajkwa Deposition Area and by lowland forest clearance and settlement.

year	Ajkwa Deposition Area (km^2)	Cleared and settled land (km^2)
1988	16	44
1996	73	158
2004	166	203

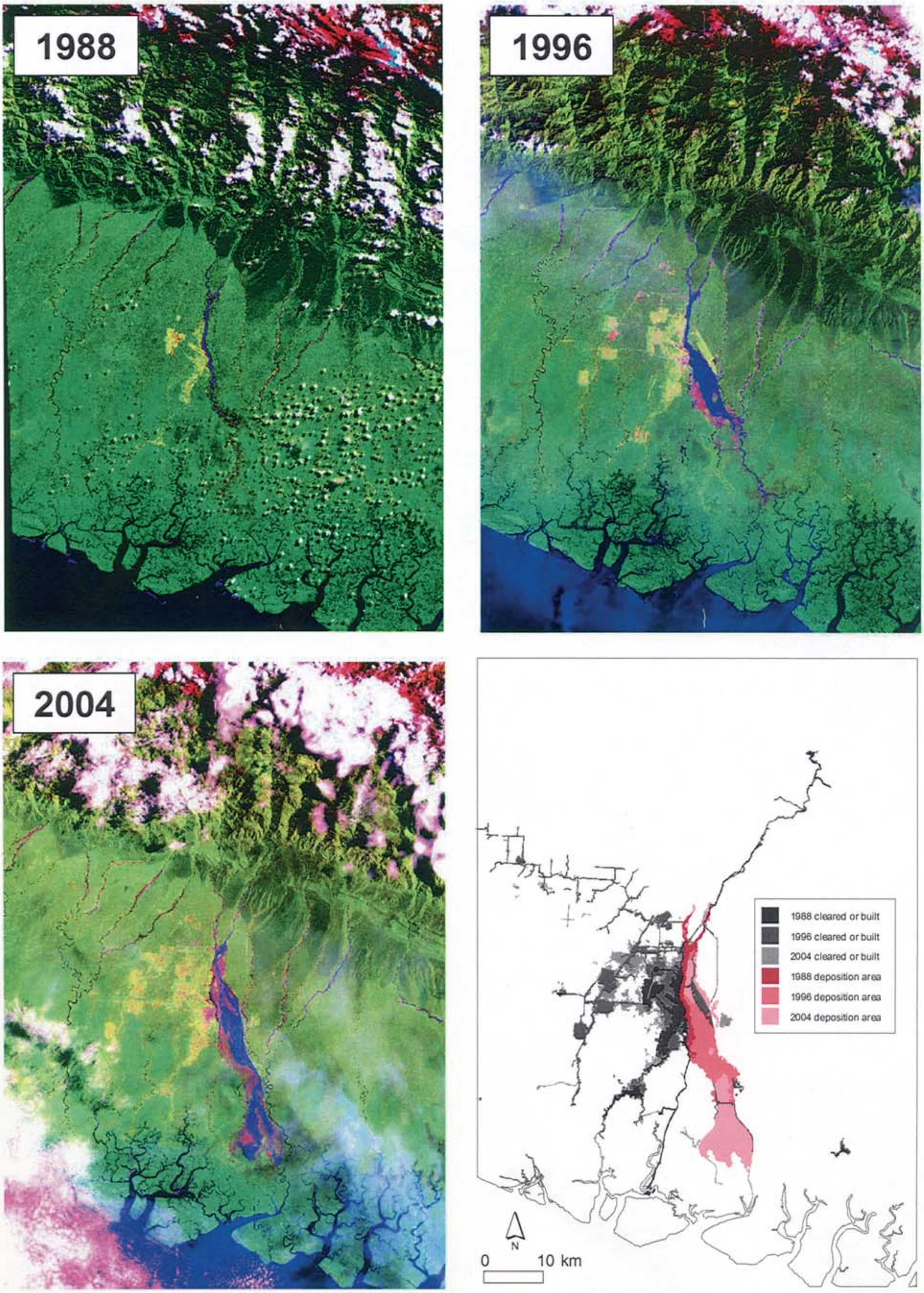

Figure 4 Major anthropogenic land cover changes to the Timika region, 1988-2004. Landsat 5 false colour composite display: red channel Band 5 (1.55-1.75 μm), green channel Band 4 (0.76-0.90 μm), blue channel Band 1 (0.45-0.52 μm).

the Rimba Irian Golf Club at Kuala Kencana between 1988 and 1996. Of particular interest, however, was a road network that materialized in the northwest of the study area on the coastal plain between 1988 and 1996, and that was extended by 2004. We have interpreted this network to be associated with the forest usage rights and licences that have been mapped by Forest Watch Indonesia and are available at http://www.papuaweb.org/gb/peta/fwi/index.html. If logging activities conducted around these roads are going to be followed by human settlement, which is a reasonable assumption, then this development has the potential to open up a further 450 km^2 of lowland rainforest to landscape transformation. According to Forest Watch Indonesia (2004) there are three sets of logging rights and licenses issued in the Timika area, covering a total area of 4500 km^2. There are reports also of the accessing of these forest areas for the extraction of *gaharu* (eaglewood or agarwood, *Aqualaria* spp.), an extremely valuable tree resin (Barden *et al*., 2001).

Discussion

Our analysis clearly demonstrates the value of using Landsat imagery for monitoring the environmental impacts of mining in remote locations, even in the tropics where cloud cover can be a constraint. The manual image classifications undertaken for this study were backed up by detailed field work conducted in 1997-1999. Major land cover types could therefore be identified and used to guide the interpretation of all three of the images used in our analysis. Furthermore, the scale and clear nature of the changes associated with this very large mine is such that any minor errors in terms of the extent of the impact area are likely to be negligible. In this sense, independence is much less an issue than it would be in cases where the causes and nature of landscape changes are not so easily attributed to human activity. One error that was not accounted for in our study, and which is common to all such multi-temporal analyses, is that errors from one year can be repeated or even compounded in the interpretation of scenes from subsequent years. Nevertheless, we do not consider that this should be any greater problem in the manual classification approach employed here than in automated approaches of supervised and unsupervised classification.

We were thus able to quantify the combined anthropogenic impacts of fluvial disturbance in the ModADA, clearing and settlement around Timika, and the establishment of a logging road network in the northwest, all of which have greatly transformed land cover in the past and will continue to do so in the future. The dominant processes of change that have operated until now have been dissection and perforation but it is obvious that in the near future fragmentation, shrinkage and attrition will become dominant as the landscape matrix converts from undisturbed lowland tropical rainforest to a human-induced cover.

The levee system surrounding the original ADA was intended to eventually enclose 133 km^2 (Mealey, 1996), while Freeport McMoRan (2004b:4) stated that the ModADA currently covers 146 km^2. Our analysis has revealed that it already exceeds this area by 20 km^2. With a projected mine life through to 2041 it is undeniable that the ModADA only offers a temporary solution to Freeport's problem of storing the estimated 3×10^9 t of tailings that will be transported by the Ajkwa to the ModADA mine tailings from Grasberg over the total life of the mine (Leith, 2003). Montgomery Watson (1999:14) implied this when they described how the portion of tailings to be deposited in the Ajkwa estuary and Arafura Sea will rise from an estimated 5% in 1999 to approximately 33% "over time". In the future the ModADA can be expected to expand further to replace ultra-biodiverse lowland tropical rainforest. Future resource plans announced by Freeport for the ModADA include the creation of settlements on arable land, natural vegetation regeneration and even potential reworking of the sediments for ore extraction if new technologies permit (Mealey, 1996; Freeport McMoRan, 2004b).

From the above analysis it is clear that the Kamoro people in the lowlands have been heavily impacted by the growth of both the ModADA and cleared areas. Kamoro have consistently been marginalised in terms of mine employment and formal sector involvement generally. In May 1997, for example, there were just 134 Kamoro PTFI employees, less than five percent of the workforce. The in-migration is predominately by non-Papuans (either as employees, official transmigrants into the SP areas, or so-called 'spontaneous' migrants from other parts of Indonesia), or non-indigenous Papuans. Indigenous communities throughout Melanesia and much of the region are heavily dependent on land as a physical, subsistence and cultural resource, and it also plays a central role for the construction of identity and the building of social relationships (Ballard, 1997; Banks, 2002). As a result of the sedimentation, Kamoro have lost access to extensive areas of forest, rivers and sago stands. In many respects the clearance for settlement is likely to have an even greater impact on the Kamoro, as this settlement is associated with the in-migration of non-locals noted earlier. It is the economic and political marginalization of the indigenous Papuan communities of the CoW area that holds the greatest danger; these communities have gone from making up greater than 95% of the population in the CoW area in 1967 to less than 15% today (UABS, 1998b).

The method employed above is useful for the identification of those areas impacted by sediment, but more sophisticated analysis with hyperspectral scanners and/or ground-truthing could reveal much more about the chemical make-up of the tailings areas, about more subtle impacts on adjoining forest and river areas, and about possible human health concerns. In terms of the social impact, and given the importance of land to identity and subsistence in many parts of the region, the detection of land lost to sediment and migration-induced clearance needs to be complemented by fieldwork among the affected communities to provide crucial information on development progress, compensation agreements, human rights, land rights, kinship and social relationships.

Overall, our analysis has showed that despite the constraints of cloud cover that are often associated with passive remote sensors in the tropics, the use of Landsat imagery can be a powerful tool for gaining an overview of environmental and select social impacts associated with large-scale mining. Alternative sensors, such as hyperspectral instruments and radar, have the capacity to provide data on the chemical composition of mine waste material and land change in areas regularly obscured by cloud, but their imagery is not easily obtained compared to Landsat. Furthermore, the use of a multi-temporal approach allows for the monitoring of the cumulative impacts associated with mining operations. The increasing ease of access to Landsat satellite imagery allows both external and internal stakeholders, including the corporations themselves, to assess broad scale landscape transformations caused by large-scale mining operations despite the constraints of remote location or restricted access to the area.

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