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The Social and Environmental Impact of Mining in Asia-Pacific: The Potential Contribution of a Remote-Sensing Approach

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The Social and Environmental Impact of Mining in Asia-Pacific: The Potential Contribution of a Remote-Sensing Approach

Introduction

Large-scale mining is one of the most contentious development activities in Asia-Pacific in part because reliable, independent long-term data are rarely available on the impacts of the mine operations on the societies and environments within which they are located. The often remote locations are difficult or expensive for outsiders to access, and the complexity of stakeholder relationships and corporate or government restrictions on access mean that broad, long-term and in-depth studies of the environmental and/or social and economic impacts are rare.

As a result, these mines are frequently contested arenas, and a number of them have become the site of claims of devastating environmental impacts and human rights abuses (Ballard and Banks 2003). While this has raised the profile of several mine operations, this notoriety has usually led to little in the way of a thorough understanding of the context of the mines' impacts. A wide range of interests ('stakeholders'), often with their own particular perspective and discourse, focus on specific local issues at particular points in time, but it is difficult to gain an overview of the project and its impacts. Hence the negative environmental and human rights stories from communities, filtered through Non-Government Organisations (NGOs), compete with corporate and often government accounts of development achievements (schools, aid posts, etc), but usually a complete account of change in communities and environments is not presented. Reliable local scale data (census, etc) are often absent, and there is generally a focus on direct mine impacts (negative and positive) without providing the context of broader changes in social and environmental landscapes.

The aim of this working paper is to explore the potential contribution of remote sensing to inform the analysis of social and environmental impacts of large-scale mines in Asia-Pacific. Four mine sites will be examined using a mix of commercially purchased and freely available satellite imagery. One question that arises is: to what extent does freely available satellite imagery and relatively cheap software make this approach suitable for poorly-resourced NGOs and community groups interested in resource-development areas? On the surface, free imagery available over the World Wide Web (WWW) appears to be a model 'democratic technology' available to all, but we suggest below that it is not necessarily so.

The paper opens with a discussion of the reported impacts of large-scale mines that have been documented in the region, and explores which of these effects remotely-sensed data can potentially inform. The four mine sites provided as examples in this paper are then briefly introduced, followed by a discussion of the methods used in the analysis. The results section presents some of the imagery and analysis from a recent paper on the Freeport mine (Paull *et al.* in review) as well as images on the other three mine sites. The paper concludes with a discussion of the democratic potential of the technology, highlighting some constraints to its widespread application in this field.

Mining Impacts: What Can Be Seen From Space?

Satellite imagery has been widely used by the mining industry for exploration for some time (see Akhavi *et al.* 2001 and Liu *et al.* 2000 for two recent examples of this application). More recently, remote sensing and Geographic Information Systems (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, utilizing 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). All of the large-scale mines in the region use remotely sensed data for one application or another, particularly for exploration. PT Freeport Indonesia (PTFI), for example, utilize remote sensing as part of their environmental monitoring but like virtually all of these applications the data generated are not disseminated beyond highly specialized academic papers (see, for example, Ticehurst *et al.* 2001).

In what follows, a simple and straightforward methodology is outlined that allows for an overview of the environmental and social impact of large-scale mines in remote regions, based on a multi-temporal spatial analysis (see Rigina 2002 for a broadly analogous example). The application here 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.

Remotely sensed, multi-spectral data are used to discriminate different land covers, even different vegetation communities, based on their spectral characteristics. Particularly obvious on such images are distinctions between broad land cover types including urban areas, bare ground and vegetation. The latter can be classified based on electro-magnetic responses, particularly in the green, red and near infrared wavebands of the spectrum. The Normalized Difference Vegetation Index (NDVI) is one example of a method widely used for discriminating vegetation types by exploiting the relationship between absorbed red light and reflected near infrared energy. The implication of using these sorts of image analysis techniques to assess the environmental impacts of large mines is that the extent of direct impacts such as mine pits, processing facilities and other infrastructure including urban developments, are very easy to map and measure. Different forms of waste disposal, including waste dumps and tailings impoundment areas, are distinct features on the imagery. In cases where tailings are deposited into river systems, such as the Freeport and Ok Tedi mines, the fluvial changes downstream are also obvious (Paull *et al.* in review).

Many of the documented environmental effects of these large mines are less obvious, even to observers on the ground. They can include:

1. potential chemical effects such as acid mine drainage from waste dumps and tailings containment areas, and mobilisation of trace heavy metals into the ecosystem;

2. effects of sediment and chemical inputs into water bodies on aquatic ecology; and

3. effects of mine operations on biodiversity (estimated by species to area relationships and the extent of disturbance).

In these cases, high resolution multispectral imagery is able to distinguish impacts on ecosystems by tracking changes in vegetation communities and thus biodiversity. Image products from satellite platforms such as Landsat 5 and 7 are generally most useful in these circumstances to highlight areas of potential impact for further, ground-based investigations. In cases of riverine tailings disposal, satellite scenes can usefully pinpoint areas downstream which have been impacted by the increased sediment input at various points in time. Of course any such analysis is best accompanied by intensive field monitoring, a critical point we will return to below.

In terms of the social impact of large-scale mines on surrounding communities, the utility of a remote-sensing approach is potentially broader than it may appear at first. Land and the resources it contains are integral to the social, economic, political and cultural life of many of the communities around the mines in the region. Land is particularly central for communities in cultural terms (being fundamental to individual and group identity, social relationships and group formation), so loss of land (to the mine, or to migrants, and compensated or uncompensated) can potentially have far-reaching and irreversible cultural effects, and we can thus start to draw links between loss of land and cultural change. The remote-sensing approach outlined below allows researchers, activists and the communities themselves, to rapidly calculate the type and area of land lost to the mine operation. The quantification of land loss, alienation or transformation by the mine operation at different points in time, provides a basic means of assessing the extent to which the loss of land is likely to be significant for the community, especially as the imagery allows the extent of loss to be seen in a regional context.

A second major consequence of these mine developments is an almost universal large in-migration of people into the project area. One of the current authors has argued (Banks 2003) that this population increase is one of the most devastating impacts that local communities experience, at least in the Melanesian context. In part this is because the settlers alienate land (for settlement, for infrastructure and for agriculture), with the same consequences noted above as if the land were lost to the mine operation itself. But the impact of migration is often more insidious for communities because kinship ties, social relationships and identity are the central organising tenets of Melanesian society. The importance of migration is that newcomers stretch and often overextend the existing webs of social relationships to a stage where central functions within the society – belief systems, leadership, group identity, networks of exchange and reciprocity – cease to function effectively. At the Porgera mine in Papua New Guinea, locals concerned by 'faces we do not know' expressed insecurity, fear and uncertainty precisely because these 'faces' were not included in the networks of relationships that defined group and individual within the society (Banks 2003). Depending on the circumstances, local communities can become minority groups within their own lands as a result of this in-migration. The extent to which the local population is marginalised (in population terms and in terms of loss of resources through loss of land) will obviously affect the degree and nature of impact on kinship patterns and relationships.

The quantification of land clearance and settlement growth, by providing a sense of the scale of migrant numbers, allows us then to speculate on the extent to which some of these essentially cultural issues become important through time for the affected communities. Such work also provides a basis for understanding the significance of other reported impacts including the incorporation of communities into broader economic and political frameworks, the extent to which human rights concerns may be present, and the changing nature of local-migrant relationships. Again, as with some of the less obvious environmental effects, remotely sensed images should be seen as aids or pointers towards issues or specific geographic areas for further work, rather than substitutes for grounded, participatory fieldwork with the communities, where they are accessible and the work is possible.

Introducing The Case Studies

Examples of the application of remotely sensed image analysis are given here from four large mine operations in Asia-Pacific. It is not the intention of this working paper to provide an even partial assessment of these operations. Basic background and further reading on each of the four mines follows, simply to provide contextual geographic and historic information.

The PT Freeport Indonesia (PTFI) Grasberg mine in Irian Jaya (Figure 1) is now the world's largest copper-gold mine, and indeed for some years has been the world's single largest gold producer, yielding over 3 million ounces of gold in 2003. 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, and is the lowest cost copper producer of any of the large mines (Freeport McMoRan 2004). 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 construction began in 1967 and production commenced in 1972 (Wilson 1981, Mealey 1996).

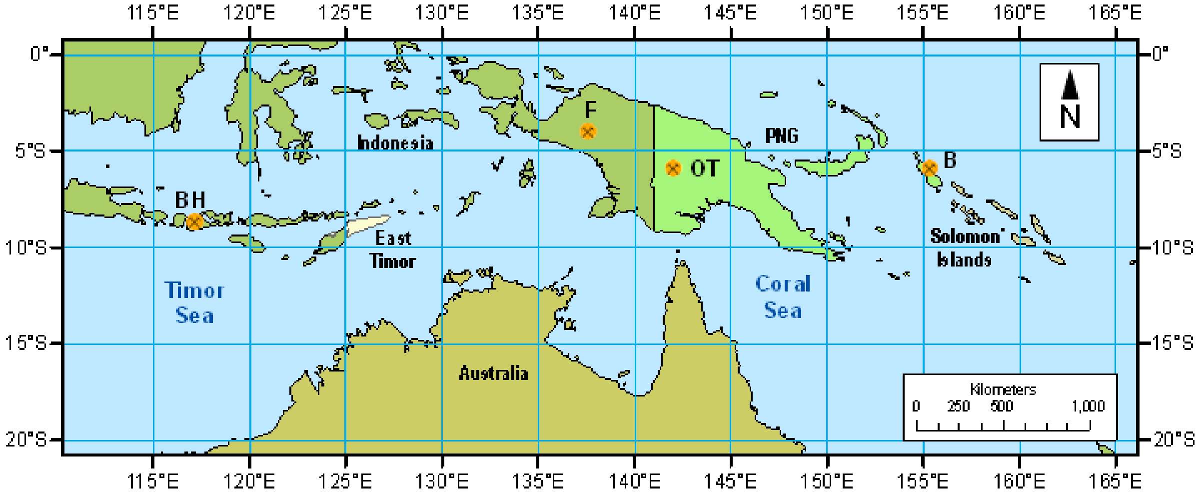

Figure 1 Location of the four mining case studies.
BH Batu Hijau, F Freeport, OT Ok Tedi, B Bougainville

The Freeport mine has a thirty year history of conflict with the local Amungme people who live in the highlands area around the mine, and its environmental impact on the Ajkwa River downstream (the traditional lands of the Kamoro people) has also been the subject of international NGO condemnation and action (Bryce 1996, Kennedy 1997). In terms of areas of environmental impact, the euphemistically labeled Modified Ajkwa Deposition Area (ModADA) in the lowlands currently covers about 166 km^2. Less obvious, but also of concern, is the impact of the mine operation and supporting infrastructure (including large camps, towns and waste dumps) on the highland environment, located adjacent to the Lorentz National Park, and within the traditional lands of the Amungme people. The mine is majority owned and operated by Freeport McMoRan Copper and Gold, a New Orleans-based company, with minority shareholding from Rio Tinto and Indonesian interests. At this stage mine closure is anticipated for approximately 2041 (Freeport McMoRan 2004).

The Bougainville Copper mine began operations at the same time as Freeport. It is located in Bougainville Island, Papua New Guinea (Figure 1), and was operated by Conzinc Rio Tinto, now Rio Tinto. The mine processed approximately 80 000 t/day and was easily the largest and most profitable enterprise in Papua New Guinea at Independence in 1975. By 1988 the mine had produced AUD$3 billion in copper and gold, but had also alienated a large section of the local community. A series of increasingly violent protests against the mine led to its closure in 1989 (for history of the mine and its closure, see Filer 1990, Denoon 2000, Connell 1991). At the time of its forced closure there was an additional 10 years of mining. The civil war that was sparked by the mine closure raged for 10 years and although largely peaceful now, tensions remain high on the island. There are no plans to reopen the mine at present.

Batu Hijau is a new mine on the island of Sumbawa, Indonesia (Figure 1) operated by Newmont Mining Corporation. Construction of the large copper-gold mine began in 1997 and commercial production began in 2000. The mine is 80% owned by Nusa Tenggara Partnership, a joint venture between Newmont Indonesia (56.25%) and an Indonesian registered company controlled by Japanese interests (led by Sumitomo Corporation). The mine is in a relatively undeveloped part of the island, at an altitude of 450 m, and located approximately 15 km inland. It is designed to process up to 145 000 t/day, and in 2003 produced around 360 million pounds of copper and 275 000 ounces of gold (Newmont, n.d.). Tailings are disposed of offshore via a submarine tailings disposal system, while waste rock is stored in dumps close to the mine site.

The Ok Tedi mine, operated by Ok Tedi Mining Limited (OTML) is a large-scale copper-gold mine in the Western Province of Papua New Guinea (Figure 1). Mill throughput has averaged 80 000 t/day since the late 1980s. From this time it has been the focus of a dispute over its impact on the Ok Tedi and Fly River systems. The origins of this dispute date back to 1984 when efforts to secure the tailings from the mine were abandoned following the collapse of the site of the proposed tailings dam. As a result tailings have been discharged directly to the river system for the last 20 years. A lawsuit in Australia against Broken Hill Proprietary Limited (BHP), the then majority shareholder in the operation, was led by Yonggom landowners from the lower Ok Tedi River area, and ran between 1994 and 1996 (Banks and Ballard 1997). The out of court settlement involved various compensation packages and a commitment by BHP to implement a feasible tailings containment option as soon as practical (Banks and Ballard 1997:Appendix 1, BHP 1999:13). In mid-1999 however, BHP announced that none of the options being considered (including immediate closure) would provide a marked improvement in the downstream environmental situation (Firth 1999). BHP withdrew from the project in 2002, handing over its 52% shareholding to a Trust company (the Sustainable Development Program Ltd) that holds this equity on behalf of the people of Papua New Guinea. Mine closure is currently officially slated for 2010.

The four mines provide a variety of settings and a range of impacts that allows for the assessment of the potential utility of Landsat imagery in different settings. Batu Hijau is a new mine, utilising Submarine Tailings Disposal (STD), while Bougainville (closed for 15 years), Ok Tedi (open for 20 with another 5 years to run), and Freeport (operating for more than 30 years with at least that long to go) all employ (or employed in the case of Bougainville) riverine tailings disposal.

Methods

Four examples are given here of the utility of Landsat imagery to mine impact assessment. The first of these, dealing with the impact of Freeport McMoRan copper-gold mine in Papua, Indonesia, utilized Landsat imagery that was purchased from commercial providers. The second, third and fourth examples, dealing with the Bougainville copper mine in Papua New Guinea (PNG), the Batu Hijau copper-gold mine in Indonesia, and the Ok Tedi copper-gold mine in PNG, drew on imagery freely available over the WWW, from a National Aeronautics and Space Administration (NASA) sourced MrSID site in a JPEG format. To date we have only comprehensively processed the Freeport imagery; the Bougainville, Batu Hijau and Ok Tedi examples are given to illustrate the further potential of the method.

In the Freeport case, three Landsat 5 images were acquired for the purpose of monitoring land cover change in the Timika region (Figure 2). 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 eight year intervals. The technical details and treatment of the imagery are fully described in Paull *et al.* (in review). 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 Australian Centre for Remote Sensing (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 its east.

To quantify anthropogenic land cover changes, polygons were manually screen digitized from 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 tailings deposition area, currently labeled by Freeport as the ModADA. False colour composite displays 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 (Figures 3a-c). 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. As a result of this methodology we were able to distinguish between natural and mine-sourced sedimentation, and to map forest clearance. The analysis was restricted to the lowland below the 50 m contour and did not include the highlands or offshore areas (largely due to cloud constraints). It should be noted, however, that both of these latter zones also experienced change during the survey period. In the highlands, this included substantial areas of mine infrastructure, towns and growth of indigenous (Amungme) settlements.

In the case of the offshore impacts, Leith (2003:168) noted a report that utilised Landsat 7 ETM imagery and found that up to 840 km^2 of nearshore environment was "polluted" by tailings in 2000.

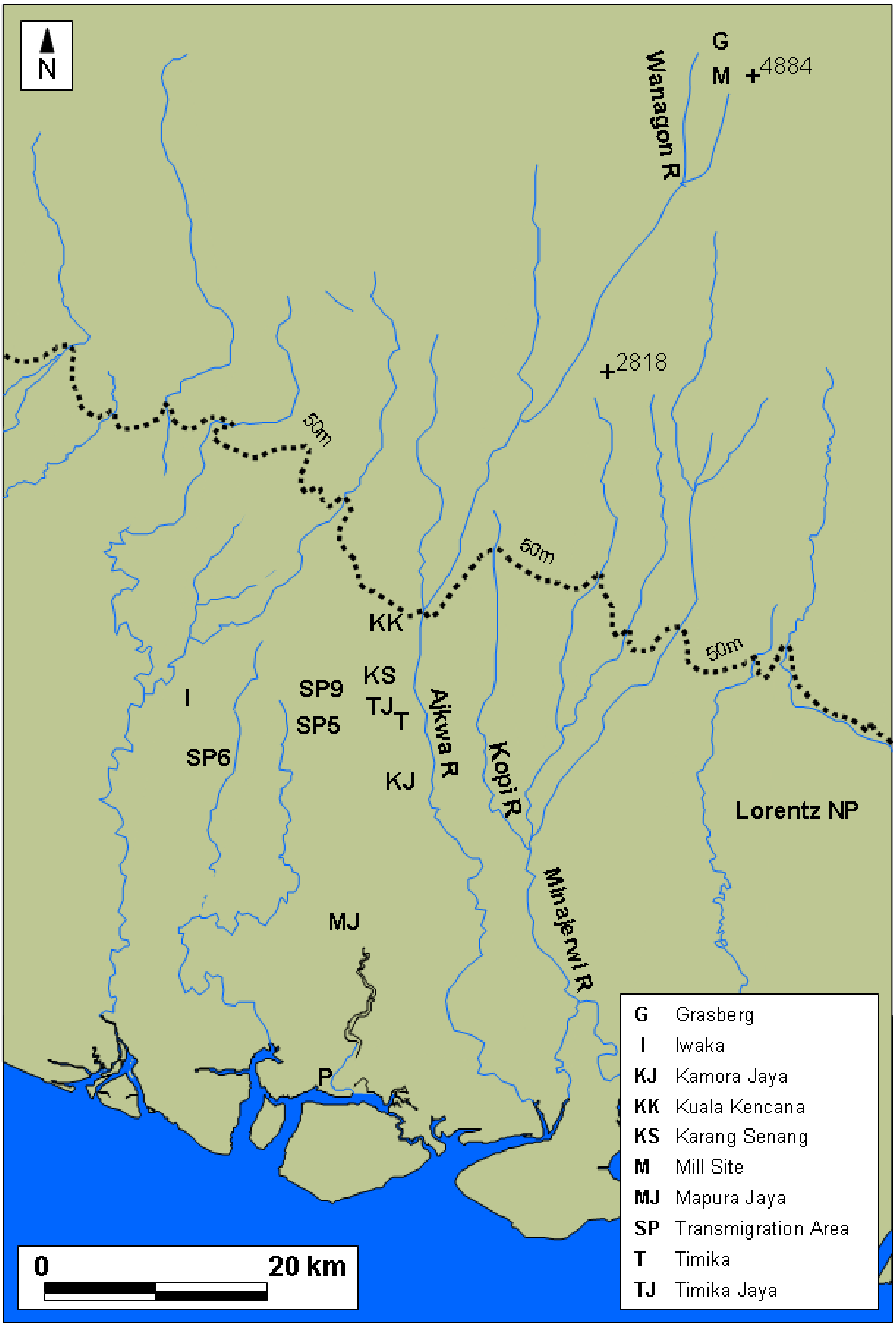

Figure 2 The Timika region showing its location and major physiographic and cultural features referred to in the text. The 50 m contour illustrates the approximate divide between lowlands and highlands.

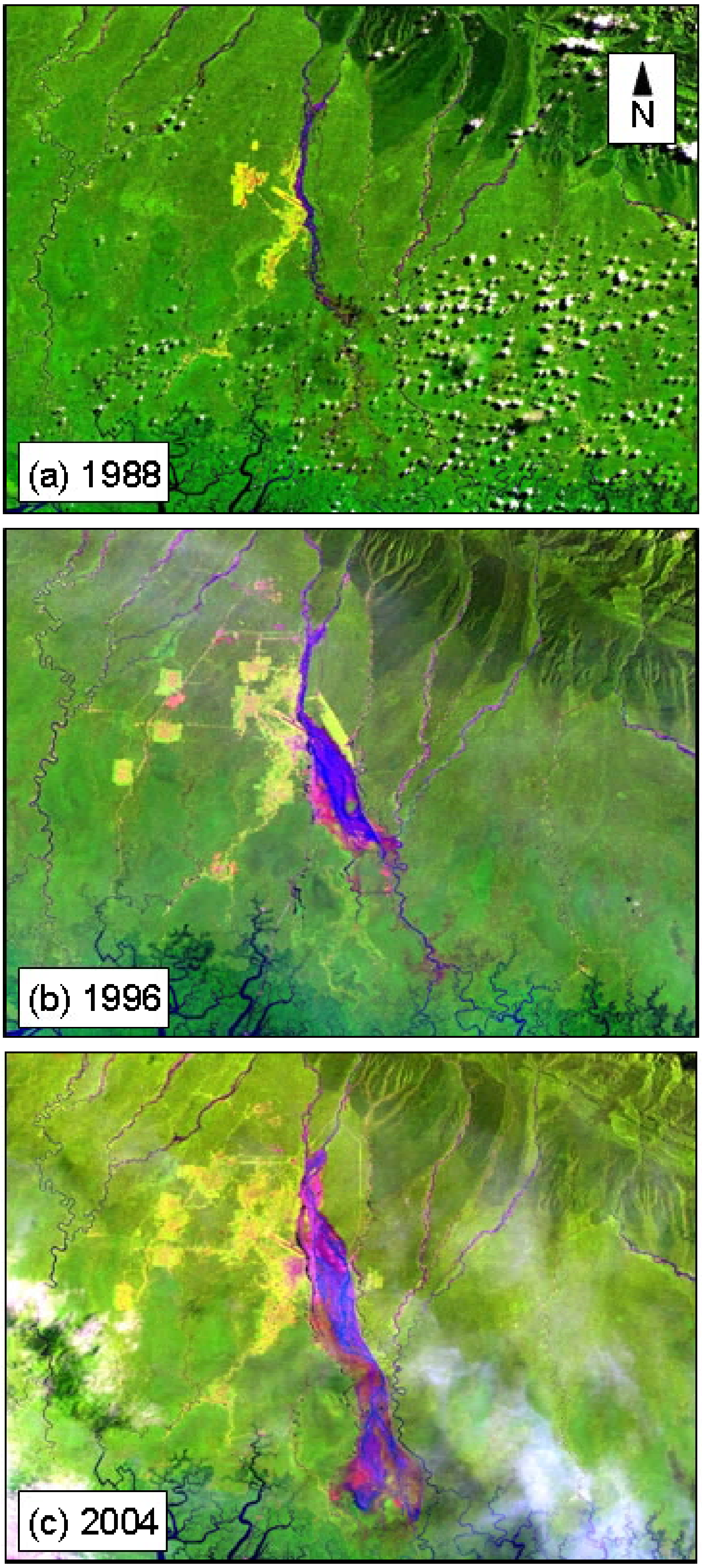

Figure 3 Land cover change in the Timika region in (a) 1988, (b) 1996 and (c) 2004. Major transformations visible in the images are to forest cover from clearance and the fluvial system of the Ajkwa River due to the sediment input from mine tailings.

For the other three mine operations, the images presented below in the Results section are in JPEG image format downloaded from a NASA website known as MrSID (NASA n.d.). This site offers coverage of most of the land area of earth for two time periods, separated by approximately one decade (*c.* 1990 and *c.* 2000). The coverage of particular regions can be downloaded as large mosaiced satellite images (rather than the JPEG images utilized here) and imported into most standard remote sensing or GIS software packages for further manipulation and analysis.

For the Batu Hijau example, a Digital Terrain Model (DTM) was developed from data acquired by the Shuttle Radar Terrain Mission (SRTM), also available at the MrSID site. This is particularly useful for visualisation purposes as it allows, in combination with the satellite imagery, a three dimensional representation of the impact of the mine operations on the landscape. This can be a powerful visual tool for activists and potentially holds further utility for researchers, governments and the corporations themselves.

Results

Freeport

In the Freeport case the analysis focussed on two broad types of landscape change in the lowlands: the sedimentation from mine-sourced tailings in the Ajkwa River immediately east of Timika and the clearance of forest for settlement and agriculture in and around Timika (Figure 4). In 1988 the sedimentation in the Ajkwa River system immediately east of Timika (in the location of what was to become known as the Ajkwa Deposition Area or 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 conclusion that the substantial disturbance to the Ajkwa River immediately east of Timika at this time 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 5). 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 reflected a six-fold increase between 1988 and 1996 to the average throughput from the mill to 125 000 t/day (Figure 5). 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 Contract of Work (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 3a-b.

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 (Figure 3b-c). By 2004, the now-renamed 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 5). Anastomosing of the streams within the ModADA was highly pronounced in the 2004 scene (Figure 3c).

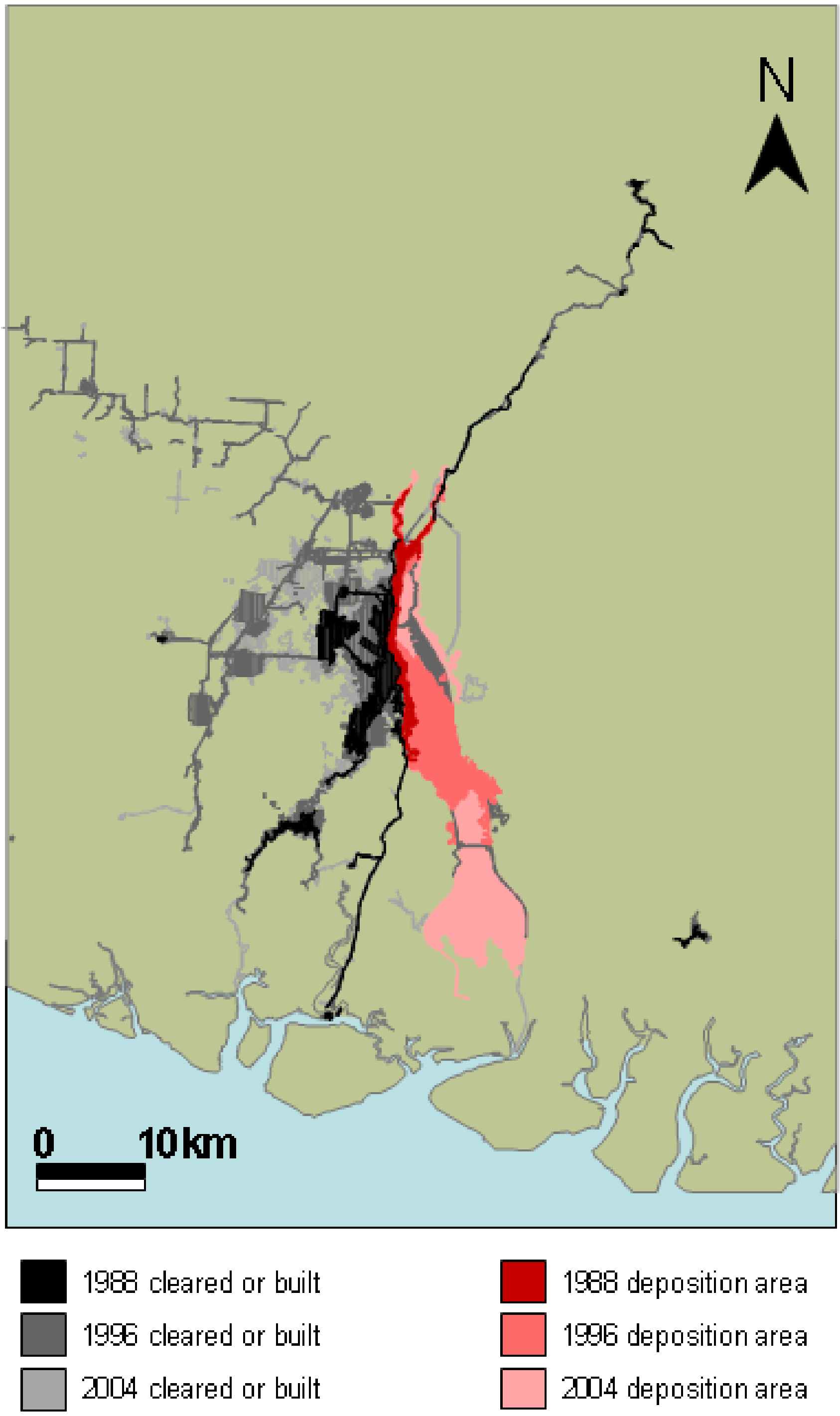

Figure 4 Summary of the major anthropogenic land cover changes to the Timika region, 1988-2004.

Table 1 Areas affected by sediment and clearance in the Timika region, 1988-2004.

Year	Ajkwa Deposition Area (km^2)	Cleared and Settled Land (km^2)
1988	16	44
1996	73	158
2004	166	203

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 (Table 1). The continuation of this trend was 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 around 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 (Figure 6a-c). 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 (Figure 7a-c), 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 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 potentially impinges on the Park itself through increased poaching of wildlife and collection of forest products.

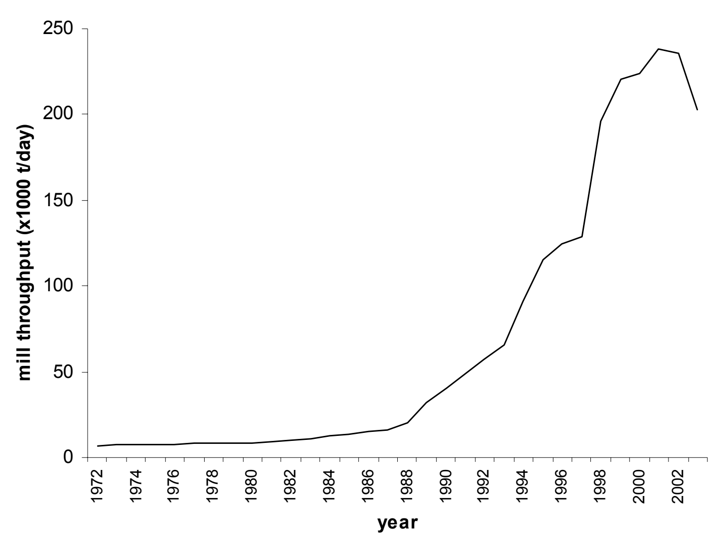

Figure 5 Freeport's daily mill throughput, 1972-2003. Sources: Mealey (1996), Freeport McMoRan (2002, 2004). The decline in throughput in 2003 was due to a large landslide within the Grasberg open pit, which forced a temporary suspension of operations (Freeport McMoRan, 2004).

Several interesting and identifiable features appeared during the period between the captured images, for example the construction of the Rimba Irian Golf Club at Kuala Kencana between 1988 and 1996 (Figure 6a-b). 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 (Figure 4), and that was extended by 2004. We interpreted this network to be associated with the forest usage rights and licences that have been mapped by Forest Watch Indonesia (2004). 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).

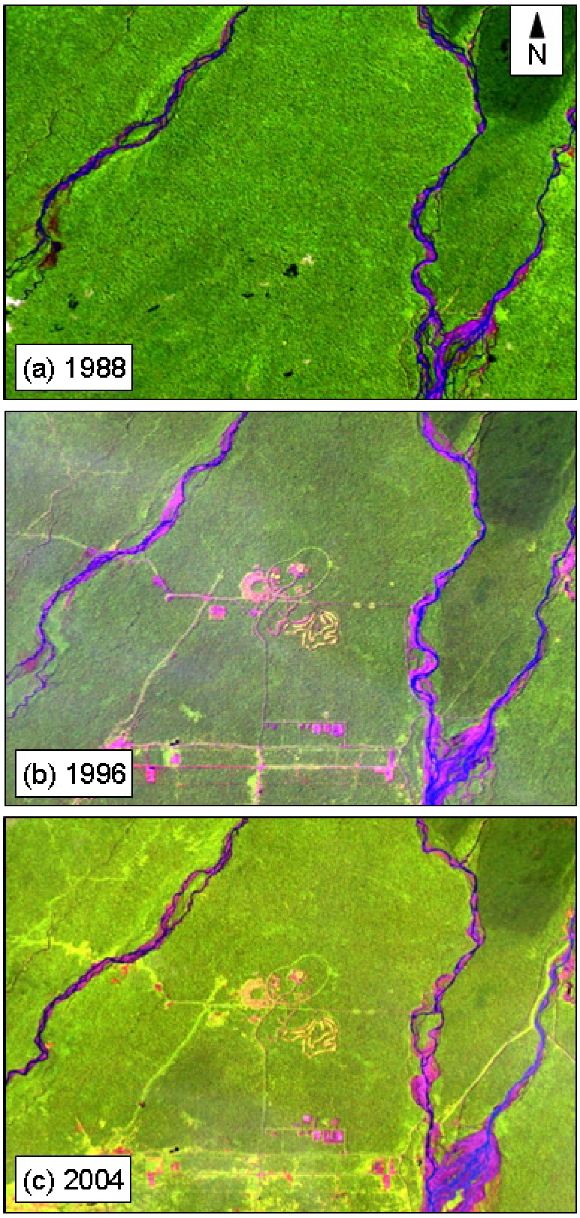

Figure 6 Kuala Kencana and surrounds in (a)1988, (b) 1996 and (c) 2004.

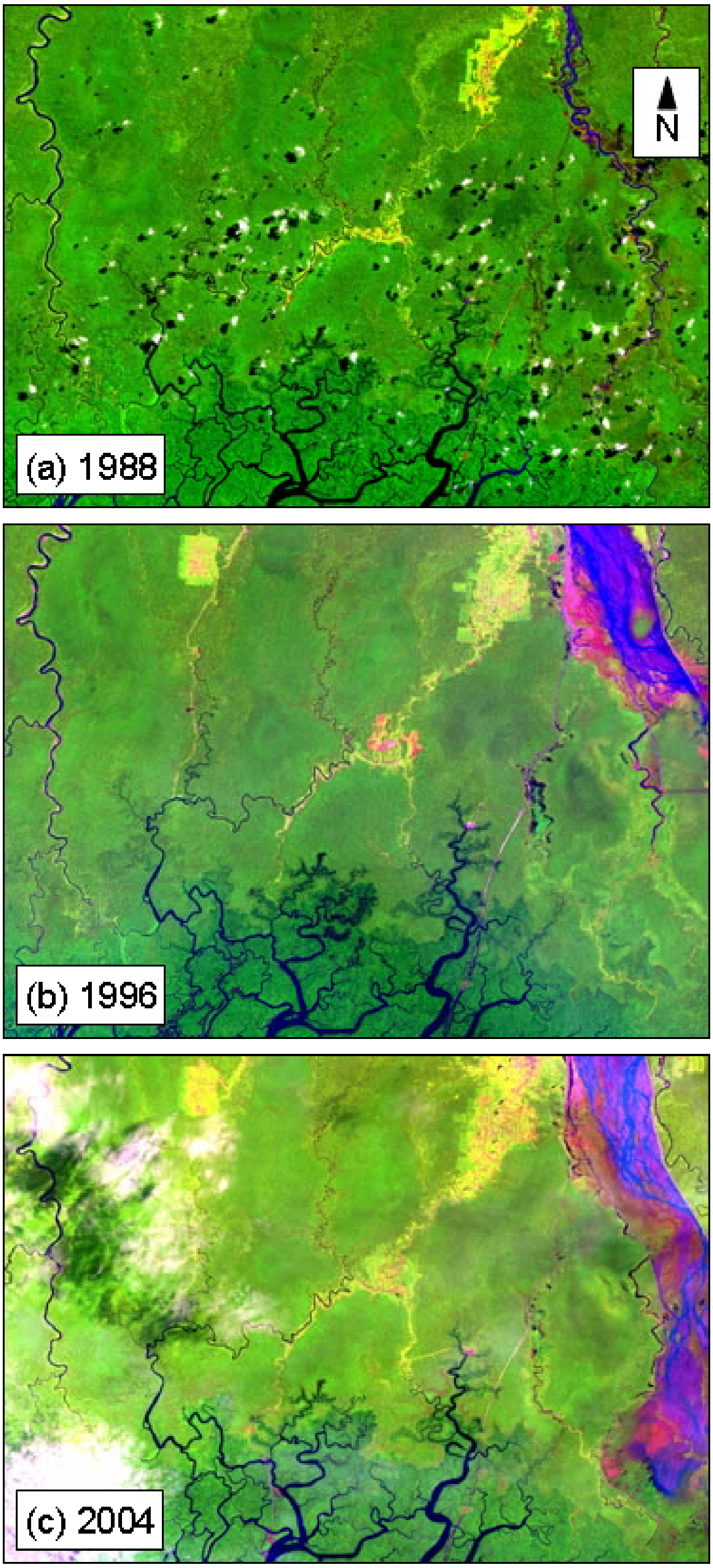

Figure 7 South Timika settlement growth in (a) 1988, (b) 1996 and (c) 2004.

Bougainville

The two Bougainville scenes (Figure 8a-b), downloaded from the NASA MrSID site (NASA n.d.), illustrate the potential utility of this imagery to monitor regrowth and regeneration of groundcover after mine closure. The first scene (*c.* 1990) is immediately after the forced closure of the mine by the local community in 1989. Here the extensive area of tailings deposition in the Jaba River to the west of the mine and the associated growth of a coastal delta is obvious, as is the mine pit and associated infrastructure in the center of the scene. The mining town of Arawa and the port site at Kieta to its immediate north are both clearly visible on the east coast of the island.

By *c.* 2000, after at least 10 years of no mining operations, much of the delta area had been naturally revegetated and the coastline substantially reshaped by coastal processes. The mine area (including the pit and the waste dumps to the immediate west) are still clearly visible, as is the large area of mine-derived waste in the upper reaches of the Jaba River. This indicates that even in these tropical environments, the large-scale landscape transformations wrought by these mines will remain for many decades. In terms of social changes, little can be deduced from the images. Interestingly Arawa in the *c.* 1990 scene appears clearly as an established urban area but by *c.* 2000 it starts to look ragged, with the urban boundary less defined, presumably due to the fact that vegetation has begun to reclaim the largely deserted town. Although it is difficult to quantify from the JPEG images alone, differences in the clearance of forest on the western side of the main divide are also visible, perhaps reflecting changes in the patterns of subsistence agriculture in the area.

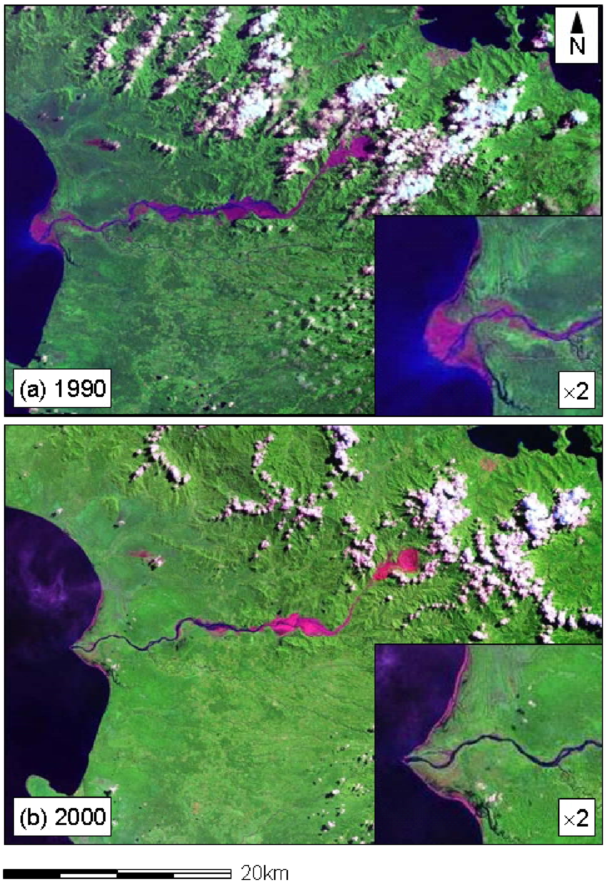

Figure 8 Bougainville in (a) *c.* 1990 and (b) *c.* 2000.

Batu Hijau

The two scenes of Batu Hijau presented in Figure 9a-b clearly show the development of the mine and associated infrastructure within the central valley. Construction began in 1997 and production in 2000, so the two scenes are able to clearly show the impact of the mine development on the local landscape. Equally striking is the urban development that has occurred along the coast to the south, and particularly to the west of the mine development. This includes a substantial port facility, and widespread conversion of vegetated areas to urban development. Figure 9c is a three dimensional representation of the area based on SRTM data and the *c.* 2000 Landsat image from the NASA site, illustrating the powerful visualisation effect of this technology.

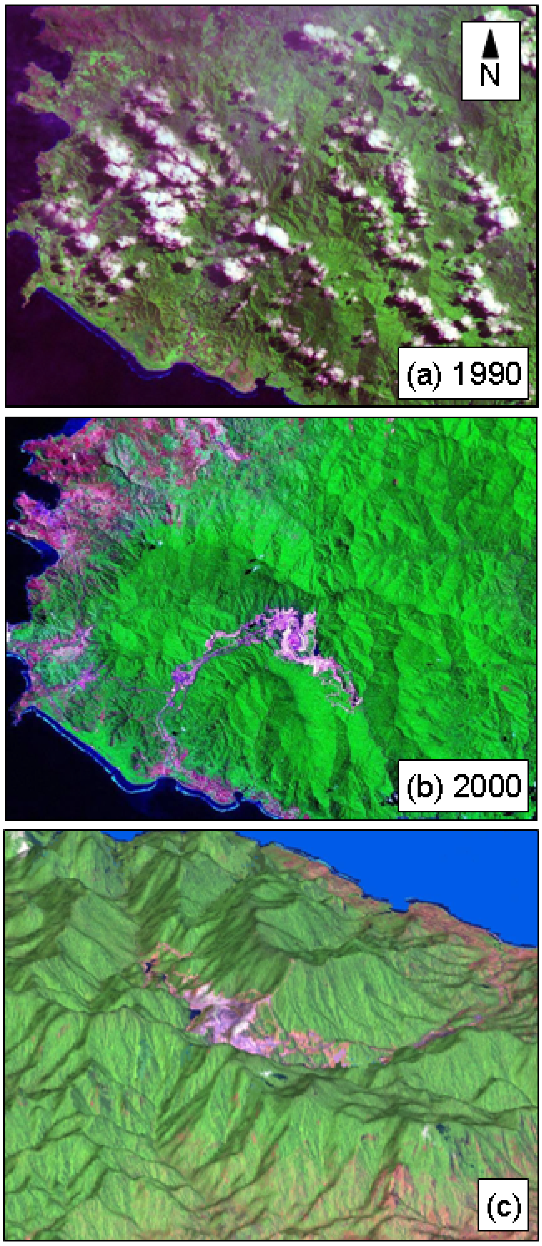

Figure 9 Batu Hijau mine, Sumbawa, Indonesia in (a) *c.* 1990 and (b) *c.* 2000. (c) a three dimensional representation of the mine based on the *c.* 2000 image and a Digital Terrain Model from Shuttle Radar Terrain Mission data, viewed from the north-west looking south east.

Ok Tedi

The focus of these images (Figure 10a-b) on the lower Ok Tedi River illustrates those areas most impacted by the tailings as the production from the mine (and tailings volumes) increased from the late 1980s. It was the Yonggom people, from the west (Indonesian) side of the lower Ok Tedi River that initiated and led the lawsuit against the Australian company BHP, then the majority owners and operators of the Ok Tedi mine (Banks and Ballard 1997). Several points of difference are obvious from the Landsat images in Figure 10. In the 2000 scene, virtually all the areas between the river meanders in the lower Ok Tedi River have been cleared or had sediment deposited on them (and now appear as bright green or pink in the false colour scenes). The extensive areas of black along the lower Ok Tedi River and its tributaries, as well as up the Fly River above the confluence with the Ok Tedi River are interpreted as areas of non-turbid standing water, caused by the bed of the main river being raised by mine-derived sediment deposition.

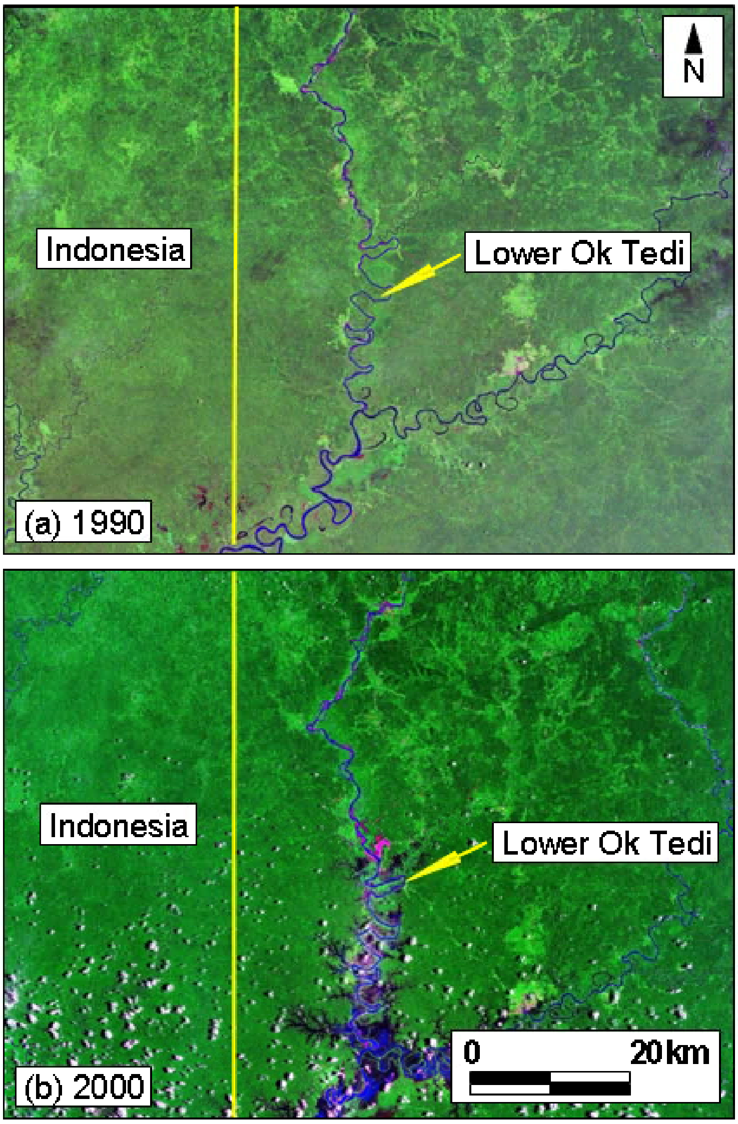

Figure 10 Ok Tedi mine, lower Ok Tedi River region, Papua New Guinea in (a) *c.* 1990 and (b) *c.* 2000.

Discussion

The four examples above show the potential utility of this method for monitoring the impacts of large-scale mining operations. The extent of mine-derived and other changes in the region can be mapped through time, allowing for an assessment of the total cumulative regional effects of these mine developments. These data are likely to be useful for internal and external stakeholders as a complement to other monitoring work, as they allow for an overview of the mine operations and their effects and impacts.

In sum, then, the examples above clearly show that we can quantify and distinguish:

- areas physically disturbed by the mine operation and infrastructure;

- areas of clearance for settlement; and
- areas to target for further ground-based investigation such as the chemical effects of tailings on regrowth and agricultural potential from both the PTFI and Bougainville examples. Likewise areas where there are potentially changes in the intensity and patterns of subsistence can be identified, such as appears to be the case in the Bougainville scenes.

From these quantifiable patterns we can then start to make circumspect comments on potentially much broader social effects – such as the effects on subsistence resources such as Sago, the potential marginalisation in the sense of sheer demographics of local communities, and some of the likely effects culturally of this in-migration and loss of land for local communities.

One point we wish to emphasize again is that we are not arguing that this technique is in any sense a replacement for grounded fieldwork. Rather by providing a very visual representation of regional and local changes through time it becomes an invaluable complement to such field research.

Limitations

The technologies utilised above are clearly powerful tools for the monitoring of physical landscape change around large-scale mining operations. Satellite imagery allows access to data that would otherwise be either impossible of prohibitively expensive to collect, and is a cost-effective way of monitoring changes through time. It is also a useful complement to field-based investigations of the biophysical or social impacts of these mines. There are, however, limitations to the methods outlined above.

Most obviously it is not a replacement for thorough, on-going, participatory monitoring and evaluation of the effects of the mine on the environments and communities around them. Even the most skilled remote sensing operator is limited to analysing the physical manifestations of change, and as discussed earlier, there is much in both the environmental and the social sense that cannot be seen through remote sensing.

Another constraint is the resolution of the technology being employed. Landsat 5 images have a pixel dimension of 30 m. Sharpening of the colour and infra-red bands by the panchromatic band reduces this to around 15 m for Landsat 7, but there are clearly phenomena of interest that will still not be visible at this scale. Satellites with much higher spatial resolution are available, for example SPOT (2.5-20 m), Ikonos (1-4 m) and Quickbird (0.6-2.8 m). An important point to consider in relation to the use of satellite imagery to monitor these mines, however, is the trade off between resolution and coverage. Given the extent of the areas impacted by these mines (usually in hundreds and, in the case of Ok Tedi at least, thousands of km^2) a finer level of analysis than that provided by Landsat coverage is expensive, resource-intensive and, ultimately, unnecessary.

A further set of constraints are attached to the apparently ‘free’ data and democratic technologies associated with access to NASA Landsat imagery. Both the NASA MrSID site and the University of Maryland Global Land Cover Facility provide access to an impressive amount of imagery, although for the Asia-Pacific region this tends to be limited to the same imagery on both sites. In the case of the NASA site this is restricted to images from two time slices (*c.* 1990 and *c.* 2000) which, while adequate for some comparisons, need to be supplemented with other time slices for most of the large mines in the region, especially where the operation is an older one, or where the operation has changed dramatically within the decade.

Connected with this is the issue of poor metadata associated with the mosaiced images from the MrSID site. It is not possible to specify exactly which year, let alone which season, the portion of the mosaic of interest was captured. This is improved with the GLCF, where metadata is available, and the range of images available is sometimes (although not often for Asia-Pacific) better. The Landsat mosaics of Asia-Pacific areas available from the NASA site are also incomplete (New Caledonia is missing from the 1990 coverage, for example), and several of the scenes are not useful for analysis due to cloud cover (such as the 1990 Batu Hijau scene, Figure 9a) or the time of day at which the image was captured.

Any analysis utilising the *c.* 1990 and *c.* 2000 mosaics from the NASA site also needs to take into account the different spatial resolutions and spectral bands that each of the mosaics offer. The former is Landsat 5 imagery, while the latter is drawn from Landsat 7 imagery and offers a finer, panchromatically sharpened pixel resolution.

Finally, unconnected with the data itself, the use of this type of analysis is also dependent on access to appropriate hardware and software to acquire, manipulate and analyse the imagery. This includes appropriate internet access to download what can be very large files (600 Mb or more in the case of some of the *c.* 2000 mosaics), a computer processor able to manipulate such large files, and at a minimum basic remote sensing/ GIS software. Some of the latter is available as freeware, but the former do still place constraints on poorly resourced NGO and community groups. A training element would also be essential in terms of both the software and basic remote sensing interpretation skills.

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