Applied Geography 54 (2014) 243–249

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Monitoring geomorphic and hydrologic change at mine sites using satellite imagery: The Geita Gold Mine in Tanzania

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Keywords:
Mining
Stream flow
DEM
Tanzania
Geita Gold Mine

A B S T R A C T

Large surface mining operations typically involve not only multiple pits but also the creation of new "mountains" of tailings. These operations dramatically change the local watershed topography and expose downslope agricultural fields and forest to tailings runoff. Given that most mine tailings expose large quantities of surface area to oxidation and transport by water, any heavy metals associated with the deposit are mobilized to move along with the runoff. In Tanzania, the Geita Gold Mine (GGM) area is such a site and the Government of Tanzania has yet to develop a water monitoring network to protect villages adjacent to the mines. As a result, mining company data are the only data available to monitor water supply and quality. Typically in mining and oil sand extraction, geospatial data are used to report and monitor land reclamation at the mining site, and while these efforts are useful, they do not consider hydrologic changes and risks. In this paper we evaluate the use of Digital Elevation Model (DEM) data from the Space shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) in an effort to identify the changes in local topography and surface hydrology around the GGM and assess the implications these changes have for the potential increased mobility of tailings and their effects upon farmers, village water supplies, and community forests using a hydrologic flow model. Results reveal that over 13 million m^3 of material has been removed from the main mining pits at GGM while over 81 million m^3 of material has been deposited elsewhere in tailings piles and waste dumps. These topographical changes have had a profound influence on the local surface hydrology, with some stream channels shifting up to 3 km from their original paths. Overall, approximately 37 km^2 of cultivated land is within the watersheds associated with potentially polluted streams and that future mining operations could impact up to 63 km^2 of cultivated land.

Introduction

Environmental regulation of the extractive industries (EI) is observed to be difficult to enforce in both rich and poor countries (Gray & Shimshack, 2011; World Bank, 2010). Much mining and oil or gas development takes place in remote places that are not easily accessed by ground transportation. It is costly for governments to do field visits and to operate on-site monitoring instrumentation (Nobi, Dilipan, Thangaradjou, Sivakumar, & Kannon, 2010). Yet open pit mining operations generate significant environmental changes because of the huge amounts of material moved and processed, and the presence of heavy metals in most waste rock and ore bodies. Erosion, competition over water resources, and quantity and quality issues, as well as, pollution of air, water, and soil are almost always the result of such operations (Razo, Carrizales, Castro, Diaz-Barriga, & Monroy, 2004).

In the Geita District of Tanzania where Anglogold Ashanti operates the Geita Gold Mine (GGM), most of the inhabitants are farmers. Several complaints have arisen from people in the mine-adjacent communities of Katoma, Nyamalembo, and Nyakabale who were concerned about the deaths of animals, human illness, and soil contamination (Makene, Emel, & Murphy, 2012). In July 2007, 17 cows died after drinking from a mine tailings pond. In Nyamalembo, people complained of frequent flooding of their farm land and their houses during the rainy season to the point that they can no longer produce enough food for their family or even raise animals. We observed that many households in the area had no chickens, an abnormal situation given that it is common to see chickens wandering around homes in these rural communities. We were also told during a 2007 interview with an elder in the area that a child had been drowned by the flooding due to the mining project. An interviewee from Nyakabale Village (to the west of the

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http://dx.doi.org/10.1016/j.apgeog.2014.07.009
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mine site) told of his wife's illness from drinking the water in the area. Other Nyakabale residents complained that water resources needed for cattle were taken by the mining company and not replaced as promised (Emel, Makene, & Wangari, 2012). Research at the University of Dar es Salaam found amounts of heavy metals, particularly chromium and lead, in the soils and plants downstream of the waste rock piles to be many times greater than World Health Organization standards (Bitala, 2007). Unfortunately, people in the area are entirely dependent upon rivers and natural springs for water supply (see Fig. 1).

Monitoring water and air impacts is the responsibility of both the state and the mining company. But many state environmental agencies do not have the resources or the capacity to undertake the duties. Even in the US, environmental monitoring often means reviewing company reports. Horowitz (2010) provides an example in New Caledonia of how mining company self-disclosure of environmental monitoring results and models of probable pollution events may have little local salience if people do not trust how the data were produced and disclosed to the community. Makene et al.'s (2012) work on water pollution and water supply issues near the Geita Gold Mine in Tanzania (our study site) illustrates that two "worlds" of discourse exist in a mining region: one populated by instruments and data stemming from mining consultants, and the other a world of local knowledge and narratives about poisons and health effects given voice by villagers. Given the distrust existing between many host community members and mining companies (and the state in many cases) there is need for inexpensive, independent monitoring capability that might be undertaken by university or non-governmental organization staff (Office of the Compliance Advisor/Ombudsman, 2008).

Remotely sensed data provide a means of providing cost-effective analyses of environmental change at mining sites (Paull, Banks, Ballard, & Gillieson, 2006; Rigina, 2002). A number of studies have illustrated the utility of remotely sensed data for examining mining related land use change (including reclamation progress) (Demirel, Duzgun & Emil, 2011), classification of tailings deposition areas (Trisasongko, Lees, & Paull, 2006), and identification of hydro-geomorphological change (Akiwumi & Butler, 2008). In a European Union-funded comprehensive assessment of the use of remote sensing for mineral resource development, Tote, Reusen, Delalieux, Goossens, and Kolodyazhnyy (2010, p. 12) claim that the "relatively small number of studies related to the environmental impacts of mining and remote sensing indicates under-utilization in this sector".

The purpose of this study was to explore the use of using freely available remotely sensed and GIS data for identifying hydrologic regime changes within a mining affected watershed. Our goal was to determine how the drainage patterns might change with the alterations in elevation caused by mining pits and by piling overburden and tailings. Additionally we created a "potential pollution" map by illustrating where tailings and runoff might flow in the Geita Gold Mine complex in northern Tanzania.

Study area

The Geita Gold Mine, situated at the headwaters of the Mtakuja River that drains into Lake Victoria, is owned by Anglogold Ashanti, a South African mining company (Fig. 2). The project, named for the biggest town in Geita Region, is a multiple open pit mining operation with potential for underground development. Mined ore is processed using a crusher, a grinding circuit, a gravity circuit, a 5.2 Mt per annum carbon-in-leach plant, and a 14-tonne stripping plant. In 2012, approximately 531,000 ounces of gold were produced. To obtain this amount, five million metric tons of ore was processed, the bulk of which became "tailings" which are piled in hills and in ponds. The amount of overburden, or rock removed to get to the ore bodies, is not included in this category but is estimated to be at least the same amount as the ore and possibly several times more (possibly over 50 Mt (see Anglogold, 2011)). The overburden is placed on the landscape near the mining pits to be "reclaimed" through grading and re-vegetation.

Large scale mining began in 1999 although the area has been a site of sporadic small-scale mining since Germany colonized Tanzania in the late 19th century. Underground mining from 1930s through the 1960s produced nearly 1 million ounces of gold. Artisanal mining is also common in the area, producing its own mélange of water and soil degradation (Mwakaje, 2012). Since 2000, Anglogold Ashanti has processed over 60 million tons of ore (our estimate). Process waste is pumped as slurry to a tailings storage facility. Water from the tailings facility is decanted and recycled back to the processing plant (Anglogold Ashanti, 2006). The process water originates from Lake Victoria and is pumped through a pipeline to the mine site.

In addition to mining, the major economic activities in the area are farming, livestock keeping and fishing. Water is very important for all of these endeavors, and in the Geita area, it is relatively scarce. Average annual rainfall is 950 mm, with Miombo woodlands, acacia species, scrubs and grasses predominant. Crops include cotton, paddy and maize. The wet season is bimodal with rains occurring from October through December and February through April. June through August is very dry with no rainfall in July during many years.

Data and methods

Remotely sensed data

Two Digital Elevation Models (DEMs) were used to measure topographic and hydrologic change in the study area over a period from February 1, 2000 to October 1, 2006. The February 2000 DEM (90 m) was derived from the Shuttle Radar Topography Mission (SRTM) (Jarvis, Reuter, Nelson, & Guevara, 2008) while the October 2006 DEM (30 m) was derived from four images from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

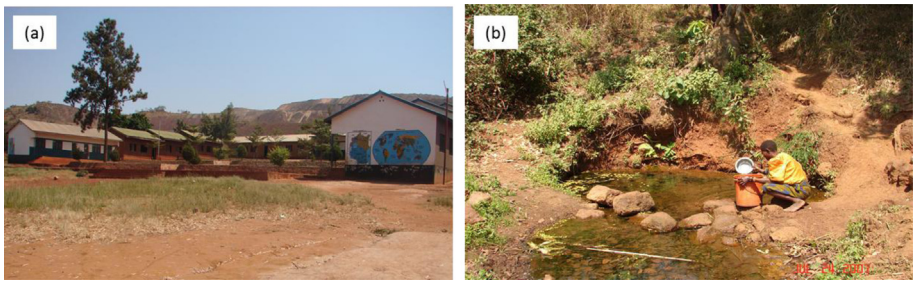


Fig. 1. Mine tailings from Geita mine, in background, overshadowing the primary school in Nyamalembo village (a), and a local woman draws water from a spring 1 km downstream from the Geita mine complex (b).

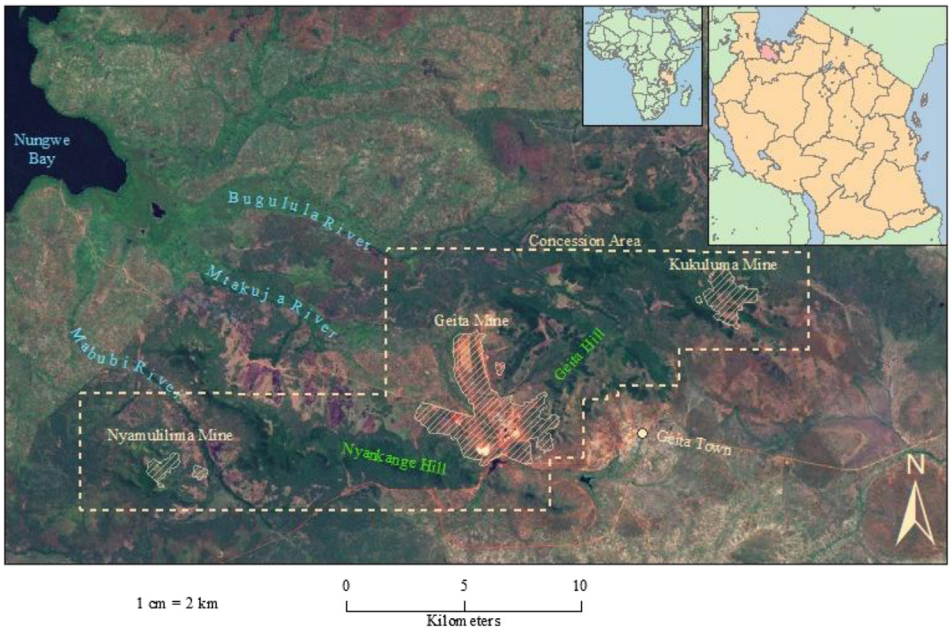


Fig. 2. Study area location in Tanzania: Geita Mine Concession (Image: Google Earth).

(NASA, 2013). For details on how the ASTER DEMs are generated see Chirico, Malpeli, and Trimble (2012). These DEMs were matched with fine spatial resolution true color satellite imagery captured on dates as near as possible to the date of the DEMs. Both images were available on Google Earth and consist of scenes from DigitalGlobe's EarlyBird 1 and QuickBird satellites; captured on March 1, 2001 and September 21, 2007 respectively (see data capture sequence in Fig. 3). Use of fine spatial resolution satellite imagery from Google Earth has proven to be a cost effective means of monitoring land cover change where in situ data are unavailable (Doris & Cardille, 2011).

Delineating active mining pits and piles

Using Google Earth, visual inspection of the September 2007 Quickbird image enabled the digitizing of polygons representing the area or footprint where mining was actively taking place when the image was captured. These active mine locations are visible in Fig. 2 and consist of locations around the mine site where vegetation has been replaced with bare soil, buildings, or infrastructure. Mine footprints were further categorized into either pits or piles. Pits are defined as features where material had been extracted from the ground and appeared as steeply terraced conical depressions with water at their base. Piles are features where mine material has been dumped for storage prior to processing or dumped as waste tailings after the extraction of gold. In the true-color satellite images, these piles can be identified by the unique textured pattern created by the individual dump truck loads of different color soil in shades of brown, tan, and red, which are built up to form gently sloped plateaus.

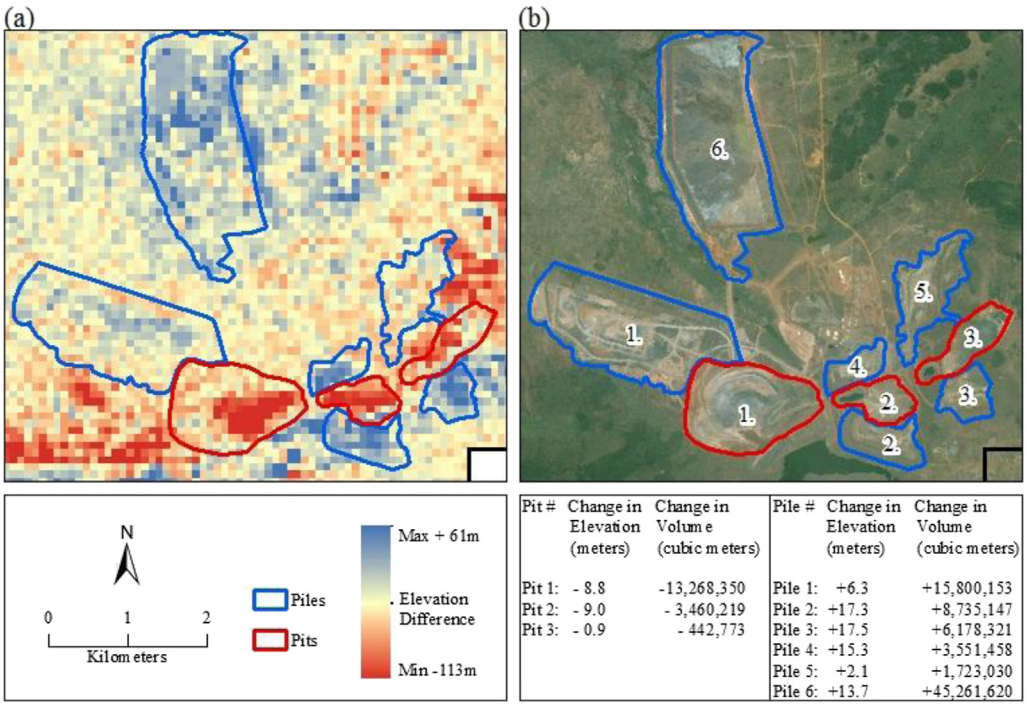
Fig. 3. Fine resolution EarlyBird and QuickBird images were acquired for the dates closest to the DEM data in order to best capture land cover change associated with mining activities. For the purposes of this study, all anthropogenic change visible in the satellite images is assumed to be present in the DEMs.

Geomorphic change analysis

To calculate the change in the size of each pit and pile, an image differencing technique similar to that presented by Blanchard, Rogan, and Woodcock (2010) was used. This technique uses a time series of DEMs to extract changes in surface height and slope in rapidly changing landscapes. First, the 90 m SRTM DEM was resampled to 30 m to match the ASTER DEM using bilinear interpolation. This was done to minimize the error associated with resampling, especially in the stream network comparison. Next, the elevation values from each pixel in the later (2006) DEM were subtracted from the earlier DEM (2000) to produce a map showing elevation change between the two DEM creation dates. Finally, the elevation change values were aggregated across the area covered by each pit or pile polygon to calculate the total volume of material either added or removed over the study period.

Stream channel and watershed generation

Stream channels were generated from each DEM date (i.e., 2000 and 2006) to illustrate how the newly formed pits and piles had changed the local surface hydrology. These stream channels were created using the spatial analysis tools available in ArcMap's Hydrology toolset. First, each DEM was edited to remove sinks or imperfections in the data using the ArcMap's Fill tool. This tool smoothes the DEM surface by filling in abnormally low pixel values that may be present due to gaps or errors in the dataset. This ensures that water that would otherwise pool on the surface of the DEM grid will flow smoothly downslope. From the filled DEM's, flow direction grids were created using the ArcMap's Flow Direction tool. The flow direction grids are based on the aspect of each DEM and contain pixels values corresponding to compass directions from 0 to 360° showing which direction surface water would flow out of any given pixel into an adjacent pixel. Once the



Pit #	Change in Elevation (meters)	Change in Volume (cubic meters)
Pit 1:	- 8.8	-13,268,350
Pit 2:	- 9.0	- 3,460,219
Pit 3:	- 0.9	- 442,773

Pile #	Change in Elevation (meters)	Change in Volume (cubic meters)
Pile 1:	+6.3	+15,800,153
Pile 2:	+17.3	+8,735,147
Pile 3:	+17.5	+6,178,321
Pile 4:	+15.3	+3,551,458
Pile 5:	+2.1	+1,723,030
Pile 6:	+13.7	+45,261,620

Fig. 4. Elevation at the main Geita mine measured by subtracting the elevation values from the Feb 1, 2000 SRTM DEM from the October 1, 2006 DEM (a), and total volume of material extracted from individual pits (−) or added to individual piles (+) (b).

flow direction from pixel to pixel was established, a flow accumulation grid was created for each DEM using ArcMap's Flow Accumulation tool. This tool assigns each pixel in the grid a value based upon the total number of pixels that are upstream and through which flow feeds into that pixel.

Visual inspection of the true color satellite images showed stream channels beginning to appear only once approximately 400 pixels (600 m^2 of land) had drained into them. The flow accumulation grids were thus thresholded to contain only pixels with over 600 m^2 of land draining into them. This produced a linear network of pixels representing areas of surface water flow with a high enough volume to be classified as stream channels. The presence or absence of stream channeling in the satellite images was based on the visual identification of riparian vegetation. The result was two stream networks; one representing the state of the stream channel network in 2000 and a second representing the state of the stream channel network in 2006, after the expansion of mining activities.

Mapping runoff pollution potential

The stream channels derived from the 2006 ASTER DEM were used to highlight the streams with the greatest potential for mine related pollution because they represent the most recent depiction of the local surface hydrology. Each stream intersecting one of the active mine area polygons (identified through the digitization of the satellite imagery discussed in section Delineating active mining pits and piles) was traced downslope to Lake Victoria or to the point where it flowed out of the Geita district.

Because each stream segment in the stream network is fed by a unique watershed (in our case a specific number and area of cells in the flow accumulation raster), we were able to use the Watershed tool in the ArcGIS Hydrology toolset to turn each of these watersheds into discrete polygons. The boundaries of each watershed polygon represent the drainage divides separating each stream channel segment. The assumption is that farmers within a given watershed will irrigate their crops from that stream segment, as opposed to crossing up and over a drainage divide. Finally, because the AngloGold Ashanti license allows for mining anywhere within the concession area, we generated a "worst case scenario" where every stream that intersected the concession area was treated as an "at risk stream" and traced down to either Lake Victoria or where it exited the Geita District.

Results

Visual inspection of Google Earth data found that the main mine at Geita had three major pits and six major piles. The largest of the pits, *Nyankanga* covers over 1.5 km^2, while the two smaller pits, *Lone Cone* and *Geita Hill* cover 0.38 and 0.49 km^2, respectively. The largest pile is the mine's Tailings Storage Facility, which is over 3.3 km^2. Results of the DEM geomorphic change analysis show that approximately 81 million cubic meters of material had been placed at the main Geita mine into six distinct piles over the study period from February 2000 to October 2006 (Fig. 4). The largest of these newly formed piles, the Tailings Storage Facility, (Pile 6 in Fig. 4) shows an average elevation increase of +13.7 m and a volumetric change of over 45 million cubic meters. Results also show that over 17 million cubic meters of material has been removed from the three main pits at the Geita mine. The largest newly formed pit is the *Nyankanga* pit, showing an average elevation decrease of 8.8 m and a volumetric reduction of over 13 million cubic meters.

The difference between the total volume of material measured in the piles and the total amount measured in the pits is roughly 64 million cubic meters. This discrepancy between the volume in the pits and the volume in the piles can be attributed to the transport of additional material to the processing plant at Geita by truck from the *Kukuluma* and *Nyamulilima* mines which were outside of our immediate study area (Turner & AngloGold Ashanti, 2005). Additionally the material becomes substantially less dense after it has been extracted due to the bulking or "swell factor" leading to higher

volume piles (DeLong, Skousen, & Pena-Yewtukhiw, 2011). AngloGold Ashanti estimates that they mined approximately 78.9 million cubic meters between 2000 and 2004 (Turner & AngloGold Ashanti, 2005). We estimate that 81 million cubic meters of material was mined between 2000 and 2006. Given that we do not account for the material AngloGold Ashanti used to fill roads, the foundation of the processing plant, the *Nymalembo* or *Mtakuja* dams, or the airport, we have reason to believe that their figures support the accuracy of our method. This amount of material is approximately 54 times the volume removed in order to build Hoover Dam in Arizona or enough to fill 32,000 Olympic swimming pools.

The effect on local hydrology from mining pits and piles is visible in the differences between the stream channels derived from the two DEMs (Fig. 5). Results show that between February 2000 and October 2006 stream channels around the main Geita mine shifted substantially. In one case, the confluence of the *Mtakuja* and the *Nyamonge* tributary shifted over 3 km upstream with implications for increased runoff and erosion as more water is forced through one channel (Slonecker & Benger, 2002; Fig. 5).

A final analysis of the 2007 stream network shows that current water purity sampling lacks the spatial coverage necessary to fully monitor surface runoff from the main mining areas at Geita. While Almas, Kweyunga, and Manoko (2009) detected heavy metals such as lead and arsenic downstream from the main Geita mine pit on the *Mtakuja* River, there are several other major stream networks that intersect the *Kukuluma* mine pit to the East and the *Nyamulilima* mine pit to the West, which are also owned by AngloGold Ashanti (Fig. 6a). By overlaying the potentially affected watersheds with cultivation maps from the 2009 Global Land Cover Project (European Space Agency, 2013) we calculate that over 37.7 square kilometers of cultivated land is at risk within the Geita district (Fig. 6b). In order to illustrate the potential future impact of mining at Geita, we generated a scenario showing the affected watersheds if AngloGold Ashanti were to actively mine over the entire extent of their concession. Overlaying these watersheds with the 2009 Global Land Cover map shows that over 63 km^2 of cultivated land within the Geita District are susceptible to runoff pollution from future mining operations within AngloGold Ashanti's concession area (Fig. 6c).

Discussion and conclusions

This paper presents a practical example of how freely available satellite data and products can be mobilized to detect and quantify mine location, geomorphic change (volume), potential hydrological change, and potential for pollution runoff. The maps provide an indication of how much the hydrologic regime has changed, and might give local people more leverage when speaking with government or mining representatives regarding their water problems. Runoff data over the years would of course be extremely desirable to have in hand in order to ascertain just how much the volumes and rates of flow have changed with mining. Yet the steeper slopes associated with the augmented piles (see Fig. 4) means that the accelerated speed of overland flows and an increased amount of sediment in streams is assured. The maps also provide an indication of the lands that might be affected by stream and overland flow, giving credence to those who suspect their soils may be contaminated. Altered stream flow patterns might be closely followed using the techniques employed in this paper to better understand how humans and animals that access water might be affected by the changed hydrologic regime. For example, the quantity of water available may be altered in a location because of changing topographic patterns, thus forcing women and children to walk further for household supplies. While remote sensing imagery cannot replace data from sophisticated instrumentation on the ground, it is surely an important source of information that university faculty and students, as well as, non-governmental organizations can use to make some assessments of hydrologic change at mining sites that might further the claims and rights of local citizens who live downstream from large mining operations.

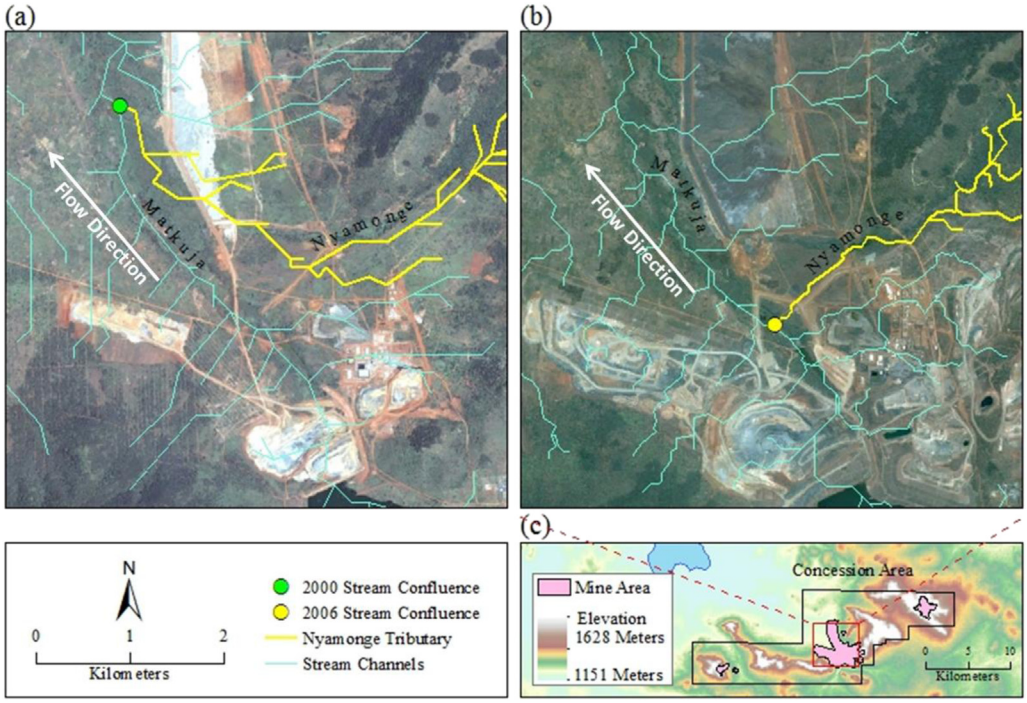


Fig. 5. Original stream channels in 2000 derived from SRTM DEM (a), modeled stream channels in 2006 derived from ASTER DEM (b), and regional topography (c).

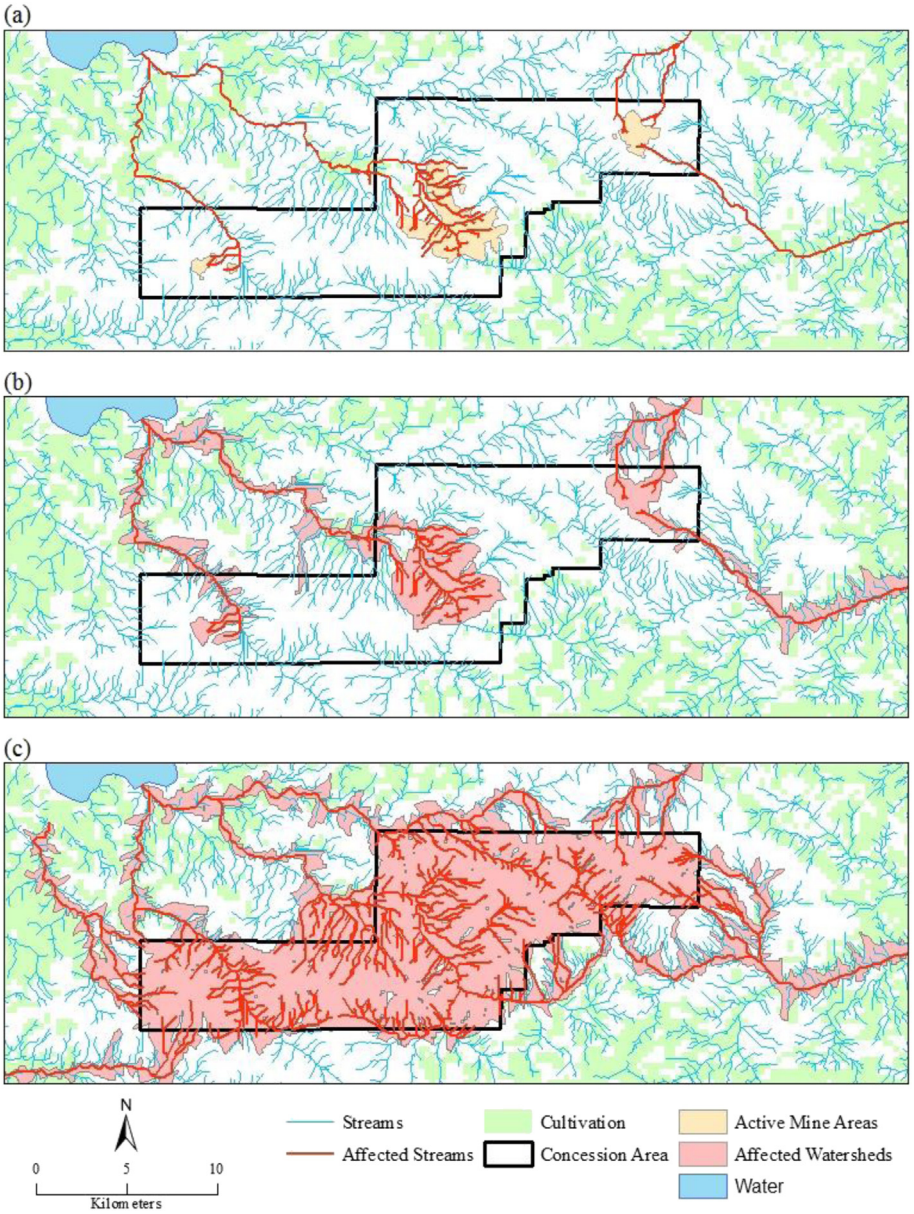


Fig. 6. Streams that intersect with active mine areas are the most likely to be at risk of pollution (a). Each potentially affected stream segment is associated with its own unique watershed (b). If mining were to take place throughout the entire concession the number of likely affected streams and watersheds increases greatly (c).

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