ENVIRONMENTAL IMPACT ASSESSMENT OF MINING BY INTEGRATION OF REMOTELY SENSED DATA WITH HISTORICAL DATA[1]

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ABSTRACT

Copper has been exploited on a large scale in the Zambian Copperbelt from the colonial period to the present, but only in recent times have the environmental impacts associated with this activity been accorded due attention. Consequently, a legacy of degradation exists. The environmental problems are compounded by a lack of funds to maintain infrastructure (both urban and in the minerals industry), leading to further degradation. Various sources of pollutants and various forms of degradation occur simultaneously, sometimes with synergistic effects. Before any remediation can take place, the overall environmental degradation of this mining district must be assessed. To this end, a study has been undertaken, and this paper forms a progress report on work to date.

Ideally, and in conventional EIAs, a dense network of sampling sites would be established. Regular samples would be collected over a period of time and then analysed. This is not feasible in the current economic climate in Zambia and so a more innovative approach is required. This paper discusses the integration of satellite remotely sensed data with historical records held by the mine. This work will provide a context for future environmental investigations and will highlight areas of degradation where urgent action is required.

1. INTRODUCTION

Primary industries such as mining and agriculture form the backbone of developing economies throughout much of the world. In this regard, countries in southern Africa are no exception. From the colonial period until the present, these countries have relied heavily on the exploitation of natural resources. Reliance on industries, such as mining, for economic survival has left vast areas of land severely degraded. This paper deals with a study focused on the area surrounding the city of Kitwe on the Zambian Copperbelt. The integration of data is illustrated by focusing on a small area in which the land use has changed significantly over the last three decades.

2. THE CURRENT STATE OF THE ENVIRONMENT IN THE KITWE AREA

Mining in Kitwe, at what was until recently the Nkana Division of Zambia Consolidated Copper Mines (ZCCM), commenced in 1926. The complex

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incorporates metallurgical plants, including a smelter, concentrators, cobalt plants, a refinery and sulphuric acid production facilities.

Waste Deposits

One of the major impacts of the minerals industry, and the focus of this paper, is the deposition of sub-economic ores and waste material on surface. Coarse wastes, such as waste rock, are usually placed in heaps (waste rock dumps) while fines, or tailings, from milling are placed behind dam walls as slurries. Tailings dams generally sterilize land by covering valuable topsoil and may also contain deleterious compounds. The tailings dams on the Copperbelt often contain compounds of copper and cobalt. When not vegetated, such residue deposits are highly susceptible to erosion due to steep slopes and the presence of fine, dispersed particles [5]. Eroded material from the dumps is deposited in neighbouring streams or on adjacent farmlands, reducing the economic potential of these resources. The tailings generally have adverse characteristics such as poor physical properties, toxic substances, nutrient deficiencies, high acidity or alkalinity, and salinity [13]. These toxic materials can contaminate rainwater passing through the tailings. On the Copperbelt tailings are currently disposed of in valley dams or dambos (wetlands). Long retention times are supposed to ensure that solids are settled out and organic compounds have decomposed before release to the environment. Despite this, seepage from tailings disposed of in these wetlands has been reported, resulting in contamination of soils and groundwater with heavy metals and acids [14].

Efforts have been made to revegetate existing dams and to rehabilitate impoundments by planting grass on the surface after closure. Environmental impacts can often be minimized by revegetation as this reduces percolation of water through the tailings, stabilizes the surface and can even make the tailings available for an alternate land use. There is evidence of erosion and low vegetation cover on dumps in the Kitwe area. This is likely to increase the suspended solids concentration in nearby streams and lead to the generation of dust. Dumps 25, 26 and 27 in Kitwe, have been very successfully revegetated [10]. The retaining walls of dump 15A have also been successfully vegetated.

3. POLLUTION

Surface Water Monitoring

Mining monitoring points have shown an increase in sulphate, copper and zinc downstream of mining areas [4]. Damage to human health is rare on the Copperbelt, but lethal doses released into rivers kill aquatic organisms in localised areas. Pollutants commonly occur at a level which causes changes in aquatic life but not total destruction. Runoff from waste rock dumps has potentially high concentrations of heavy metals and acidity.

Waste Water

Waste water from ore beneficiation is generally disposed of in tailings dams, the eluate of which flows into the Kafue River. This water is high in sulphates and generally hard. In some instances untreated waste waters enter streams, reportedly as a result of design faults and maintenance failures [14]. Consequently surface water is contaminated with suspended solids and heavy metals such as copper, cobalt, lead and zinc. Heavy rainfall in the wet season causes loss of freeboard in tailings impoundments. If these structures overflow, the uncontrolled discharges may contaminate water, river sediments and aquatic biota, especially benthos. There is, however, no record of a tailings impoundment overflowing in the Kitwe area [10]. Mine effluent from open pits and underground operations is directed into the Kafue River. Although this water is generally within applicable limits, it has a high suspended solids (SS) and total dissolved solids (TDS) load [14].

Thus receiving waters are not adequately protected from contamination. Copper in effluents which results in concentrations of 1 to 2 μg/ml in river water has removed animal life and severely reduced populations of algae and fungi in localised areas [12].

4. ENVIRONMENTAL IMPACT ASSESSMENT

Environmental impact implies a change in a natural resource. This usually due to man's activities and consequently a loss of resource, or negative impact, occurs. Thus, the measurement of environmental impacts requires the detection of change in the environment. Berger [2] lists four key questions to be answered in assessing the state of the environment.

1. What is happening to the environment: is ecosystem health in decline, steady or improving?
2. What stresses act on the environment: are physical, chemical and biological pressures increasing or decreasing?
3. What is the significance and future implication of the changes for humans and for the ecosystem?
4. How are we responding to the changes?

In seeking answers to these questions, environmental indicators are useful. These indicators can be used for assembling data on past and present changes due to natural processes and also to assess the spatio-temporal impacts of mining on the environment. Such indicators are measures of surface or near-surface processes and phenomena that vary significantly over periods of less than a century. Indicators measure environmental change rather than the integrity, health, resilience or sustainability of the environment.

There are datasets from different dates available for this investigation. The thrust of the analysis is to detect change in the environment between these dates, to infer a decrease/increase in environmental quality and then to assess the significance of these changes. To this end spatial data from maps, aerial photographs and satellite images have been integrated with conventional quality data collected by the mine.

For the purposes of this report, the discussion is restricted to a tailings impoundment west of Kitwe, dump 15A. This tailings impoundment lies near Mindolo dam, a recreation area.

5. DATA ANALYSIS

Distribution of Tailings Impoundments

The earliest data available consists of a set of four topographic maps printed between 1959 and 1967 by the Northern Rhodesian and then the Zambian Surveyor General. The maps are based on various aerial photgraphic missions, the last of which was flown in 1957. These maps were digitized and taken into Ilwis, a geographic information system (GIS). Digital information extracted from this set of maps showed that by 1957 there were 14 residue deposits in the Mufulira-Kitwe area. These covered a total of 836 ha. A newer set of maps was obtained from the Government Printer in Lusaka and digitized to assess the change in distribution of these residue deposits over time. The sheet covering Kitwe itself is a third generation map dating from 1986 (photography: 1984) while the other three maps are second generation and date from 1972 (photography: 1968). On these maps, the number of dumps had increased to 43 and the total area covered had increased almost three-fold to 2 402 ha.

The first generation maps show that no dumps were present at Mindolo dam in 1957. The tailings deposit (dump 15A) was commissioned in 1971 in what was then a wetland area. By 1984 it had an areal extent of 660 ha with another 4 deposits in the immediate vicinity covering a further 44 ha. 1996 mine data estimated 15A’s mass at 69 850 898 tonnes covering a surface area of 709.2 ha [6].

Surface Drainage

The Mindolo dam area is drained by the Mindolo stream, which flows due east towards the Kafue river, and by the Ichimpe stream flowing northwards into the Mwambashi river which flows in turn into the Kafue. The Kafue is a river of major economic importance in Zambia as about one third of the population resides in the river basin [11]. The Kafue also contains Zambia’s most productive agricultural areas and the major hydroelectric plant at the Kafue Gorge dam [11]. Before joining the Kafue, the Mindolo stream passes through the northern suburbs of Kitwe. In 1957, the urban area affected by this stream covered a total of 179 ha and a further 17 ha of informal settlements were within the stream catchment. By 1984, this urban landuse area had increased to 453 ha and the area of informal settlements to 228 ha. Thus, over a period of 27 years, the urban area influenced by the stream increased by two and half times and the informal settlements increased thirteen fold. Census data shown in Table 1 indicates that the official population of Kitwe increased by 1.5 times between 1963 and 1980. The number of people potenially affected by dump 15A has increased dramatically and consequently, the area has become more sensitive to this land use.

Table 1. **Population in Kitwe [7].**

Census	*Population*	*Growth Rate (%)*
1963	123 027	
1969	199 798	8.42
1974	251 000	4.67
1980	308 208	3.48
1990	341 912	1.04

Significant changes in water bodies have occurred. In 1957, the Mindolo dam had a surface area of 70 ha and it's principal axis was oriented E-W. By 1984, the eastern-most extent of the dam had moved west by 1 300 m and the orientation of the dam had changed to N-S. On aerial photographs taken in 1990, large deposits of tailings, not shown on the 1984 map, can be seen east of the dam. It appears as if the tailings were emplaced into the dam, displacing the water and flooding parts of the Ichimpe drainage system. This may have significant hydrological implications. In 1984 the surface area of the dam was 192 ha (a 2.8 times increase). At this date the pond atop dump 15A was even larger than Mindolo dam with an area of 244 ha.

Mine Data

Between 1988 (the earliest data available) and 1996, at least 25 337 300 t (some data missing) of tailings material was emplaced into impoundments in Nkana Division [15]. 20 158 800 t of material was emplaced at dump 15A through various pipelines. The average rate during this period was 255 175 t per month. This material had an average concentration of 0.1% copper and 0.03% cobalt [15].

ZCCM water quality data is available for the four sites at which the mine monitors water flowing from the dump/dam [16]. The sites are:

- site 627, the dump pond,
- site 628, Mindolo stream where water from the Mindola shaft (the mine's name is spelt differently) combined with water from Mindolo south dam overflow is discharged,
- site 629, the Mindolo dam north overflow and
- site 631, the quality of water discharged from the underground workings via Mindolo shaft.

From the Mindolo dam north overflow, water flows into the Ichimpe stream.

There is little water quality data for the dump pond, but a maximum TDS of 2 610 mg/l was recorded in April 1995. The TDS at site 628 varies between 1400 and 2600 mg/l and metal concentrations of up to 0.3 mg/l have been recorded. Metal concentrations in the water flowing into the Ichimpe steam are in a similar range to site 628. Total iron reached a maximum of 0.47 mg/l in January 1996 [16]. Field measurements by the author in 1996 yielded a pH value of 7.5 and an electrical conductivity (EC) of 119 mS/m. Site 631, water from undergound, also has a circum-neutral pH value average (7.81). It has a variable TSS concentration with a maximum of 94 mg/l recorded in May 1996. TDS are high with an average of 1 281 mg/l and metal concentrations are highly variable. Copper has the highest concentration (0.37 mg/l – January 1996). A pH value of 8 and an EC of 219 mS/m were measured in the field. The pH values at all these sites were above 7.5 on average [16].

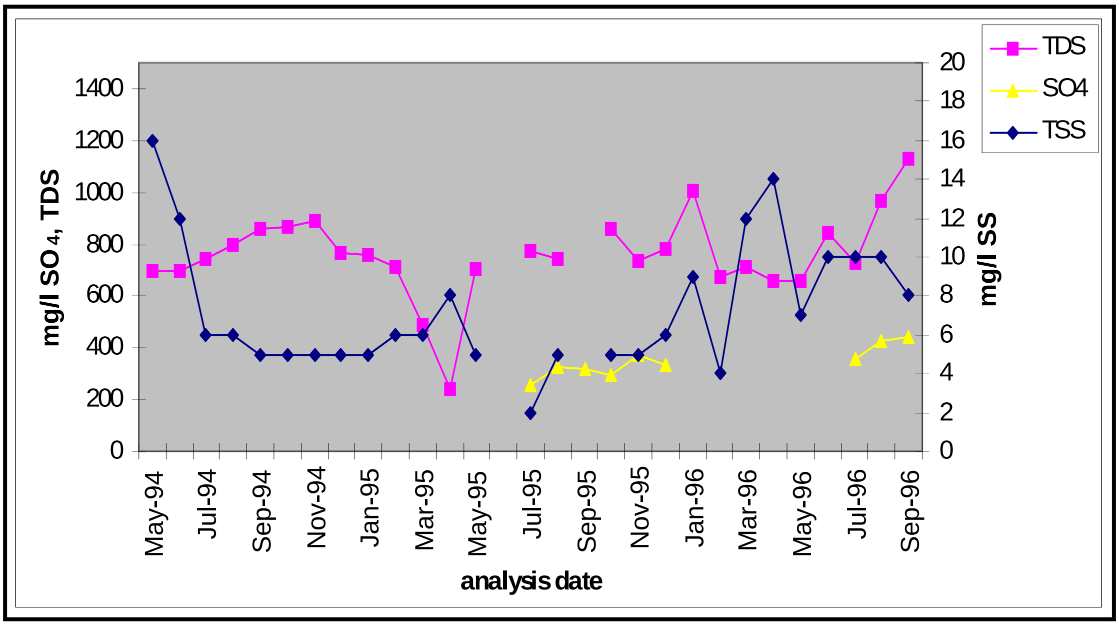

Figure 1. **Salinity analyses for site 629, the Mindolo dam North overflow [16]**

The tailings emplaced at dump 15A have high concentrations of copper and cobalt. In 1982, chronic copper poisoning of livestock resulting in the death of 270 head of cattle, 50 sheep and 140 goats occurred on farms adjacent to the Mwambashi river [12]. Copper was present in the river sediments and in riverside vegetation. Concentrations of the metal ranged from 250 to 3 800 μg/g in animal tissue and from 3 000 μg/g to 20 000 μg/g in the river sediments (Brasser & Charman, 1982 in [12]). Mwale [12] found that the copper, cobalt and manganese levels were within ZCCM's water quality limits, but exceeded those set by the European Union and the World Health Organisation. In addition, he found (by experiment) that significant concentrations of copper associated with SS were released into solution after acidification of unfiltered water samples. This metal accumulated in the sediments is believed to have been ingested by livestock, resulting in fatal poisoning.

Metal concentrations in water at the other sampling sites in the Mindolo system do not exceed the effluent limits set by the Zambian government, but are far in excess of international drinking water standards (such as the limit for copper at 0.02 mg/l or iron at 0.3 mg/l). The water also has a very high salt load as shown by the TDS, sulphate and EC analyses. While neither the Zambian limit of 1 500 mg/l for suphate nor the generally accepted limit of 500 mg/l is exceeded, TDS should be below 500 mg/l and the average value for each of the monitoring sites exceeds this. This water is unsuitable for human and animal consumption and cannot be used to irrigate sensitive crops. The Kitwe Municipality operate a drinking water abstraction and treatment plant on the Mwambashi river. The water purification equipment operated by the municipality is in a very poor state of repair [7] and there is thus a risk of reticulating contaminated water through the city. People living near the river rely directly on the unpurified river water for survival. The quality of this water is therefore a significant variable controlling the general well–being of the populace.

Remote Sensor Data

Landsat Thematic Mapper (TM) data was acquired for the dates: 1989/06/02, 1993/05/28 and 1997/05/23. These data represent ground reflectance values of the area just after the rainy season. A strong vegetation response is present and the data are good for detecting vegetation patterns.

Vegetation assemblages and plant structures are good indicators of environmental change (Bruneau, 1980, in [9]). A common method for measuring the presence and condition of green vegetation is the NDVI or normalized difference vegetation index, which is a combination of reflectance in the red and near infrared wavebands received by the satellite. Using this combination of bands (for a full discussion see [8]) an image can be generated in which vegetation reflects strongly (i.e. has a high digital number, DN, and appears white) and soil, rocks and hard man-made surfaces appear dark (low DN). In the Mindolo area, the water bodies, dumps and roads appear black, as they are free of vegetation. Agricultural fields, plantations and natural savannah vegetation appears light grey or white, depending on the density of the foliage. An NDVI image was generated for each of the three dates available. A colour composite image was then generated to assess change over this period. The results are complex and require further analysis, but show similarities in vegetation between 1989 and 1997, with 1993 generally showing more intense vegetation cover. This is not unexpected as 1993 had a maximum monthly rainfall of just over 300 mm compared to 500 mm in 1993 and about 250 mm in 1996 (1997 rainfall data was not available at the time of writing).

NDVI Analyses

The vegetated areas surrounding the dumps and the dam show a predictable variation over the period 1989-1997, with the vegetation response being generally higher in the 1993 data than in either of the other two data sets. The western retaining wall of dump 15A has a zero reflectance for all years, as do other dump surfaces (q.v. Figure 3). This is to be expected as the wall is devoid of vegetation. The first row of pixels adjacent to the wall (one pixel is 25 x 25 m) exhibit a progressive decrease in DN over the three image acquisition dates. This trend is present up to and including the third pixel line away from the wall (a distance of 75m). The behaviour of DN at this location suggests a decrease in vegetation response over time, which is not due to meteorological variation. While it must be remembered that spatial inaccuracies of up to 20 m are possible, the trend implies a vegetation die-back related to the dump. Beyond 75 m, the expected rainfall-controlled ratio is re-established.

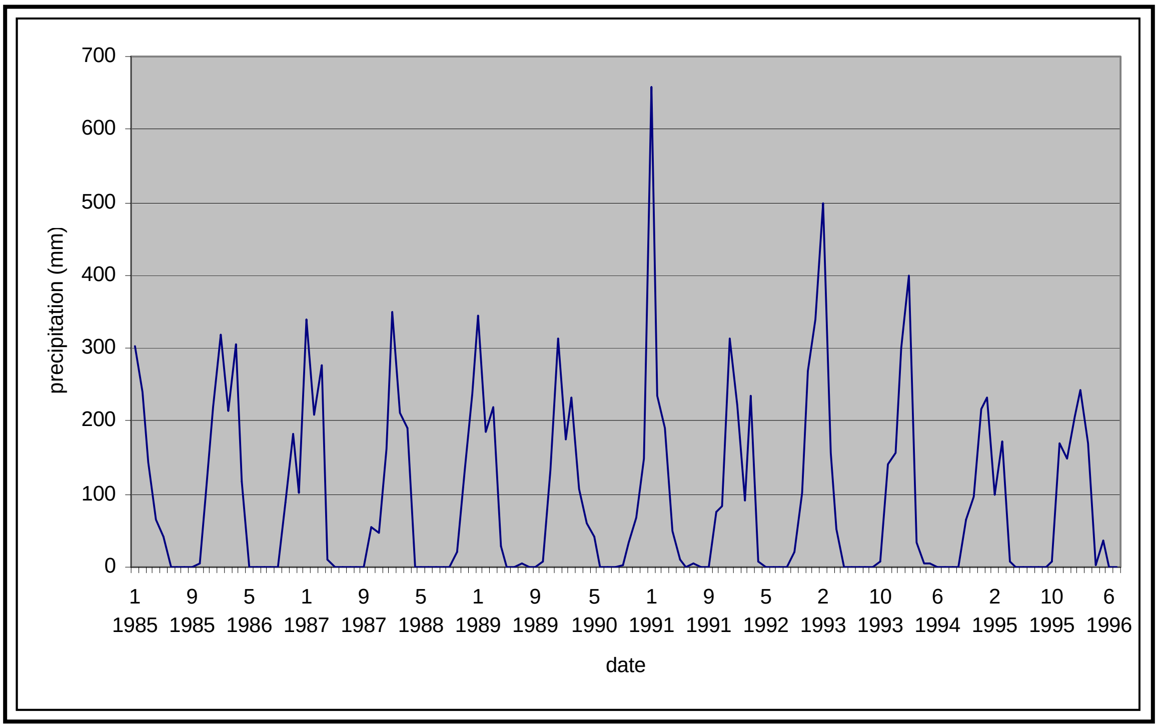

Figure 2. **Rainfall measured at Kafironda, near Kitwe (source: Zambian Weather Bureau).**

On the dump's eastern extremity, the die-back trend is not observed. Near this retaining wall, there are many mixed pixels, making interpretation difficult without further data processing. An anomaly is present in the north-eastern corner of the dump. The vegetation response is high in 1993, but non-existent in the other two years.

In all three of the NDVI images, it can be seen that the dump extends beyond the mapped southern boundary for about 800 m. This extension is 500 m wide on average. A site investigation in 1996 revealed that peasant agriculture was being conducted in fields immediately adjacent to the tailings material. The 1990 aerial photography shows that peasant agriculture is also practiced elsewhere within the demarkated confines of dump 15A. The potential for contamination of food stuffs is thus great. An informal settlement is situated about 900 m from the dump's eastern retaining wall.

The tailings suspected of displacing Mindolo dam occur in two lobes, the larger of which is in excess of 2 km in length. These are not marked on any maps. The NDVI ratios show no trend over time in these deposits, implying that they were emplaced prior to 1989. No strong trends are observed on the dam's periphery and therefore this too has been stable since 1989.

Land Classification of Satellite Images

The seven Landsat data layers (bandwidths) which comprise a data set can be statistically combined using principal component analysis (PCA). The resulting data layers are not correlated with each other and most of the real information is contained in the first two or three components (layers). This simplifies analysis of data as redundancies or repetitions are eliminated. Colour composite images were generated by combining principal components 2, 3 and 4 for each of the three data sets. This combination resulted in image vectors which discriminated between residue deposits and urban land use (often spectrally similar) allowing automated classification of the images. The resulting classified images were then used to calculate the area occupied by tailings dams.

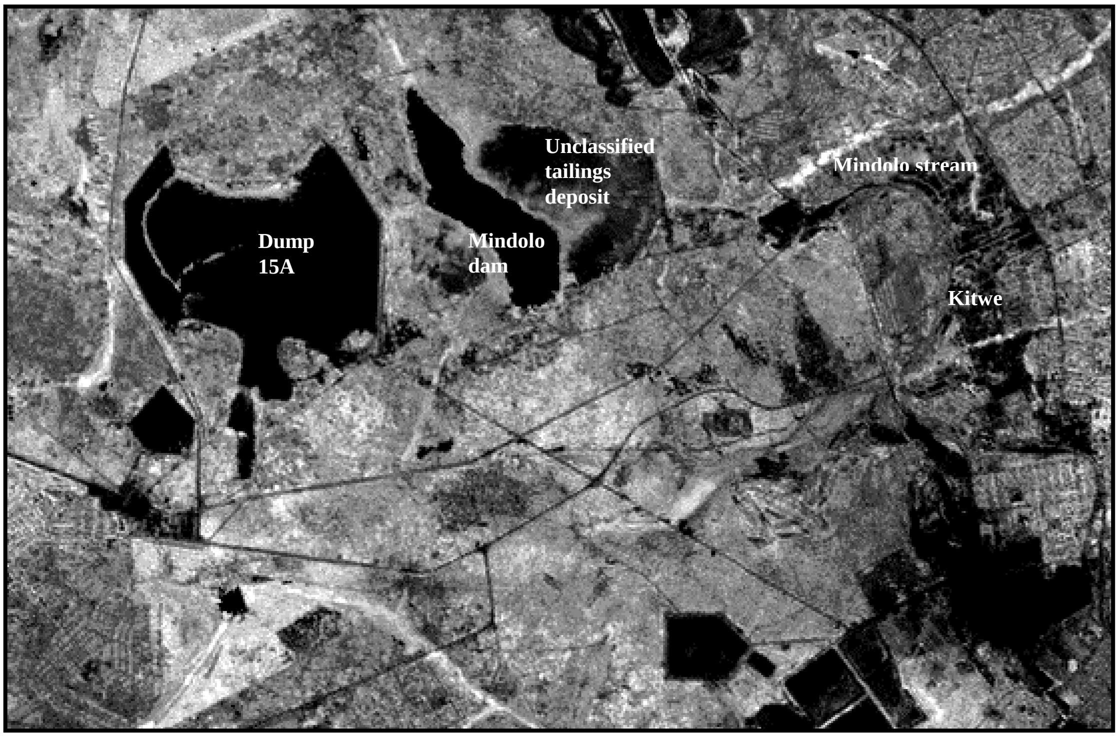

Figure 3. **NDVI image for 1997 data of the Mindolo dam area. The tailings deposit and the dam are clearly visible in black (low vegetation intensity) while streams are visible in white (high vegetation intensity).**

The land use classification results are not entirely satisfactory. The tailings deposits are detected and classified as such, but on a pixel by pixel basis. This results in any heterogeneous areas on the deposits not being classified as a tailings dump pixel. Water bodies on top of the dumps are also not classified as tailings deposits, reducing the overall area of the dump. In the 1989 data set, the area classified as dump 15A (excluding the pond) covered an area of 286.5 ha. If the area covered by the pond (244 ha – map data) is added to this, there is still a shortfall of 129.5 ha, probably due to misclassification of pixels. Classification of 1993 and 1997 data resulted in an area of 259.8 ha and 286.7 ha, respectively. The classifier is thus very sensitive to vegetation (1993 also had higher DNs in the NDVI image). Interestingly, the tailings west of Mindolo dam were not classified by the classifier in any of the images.

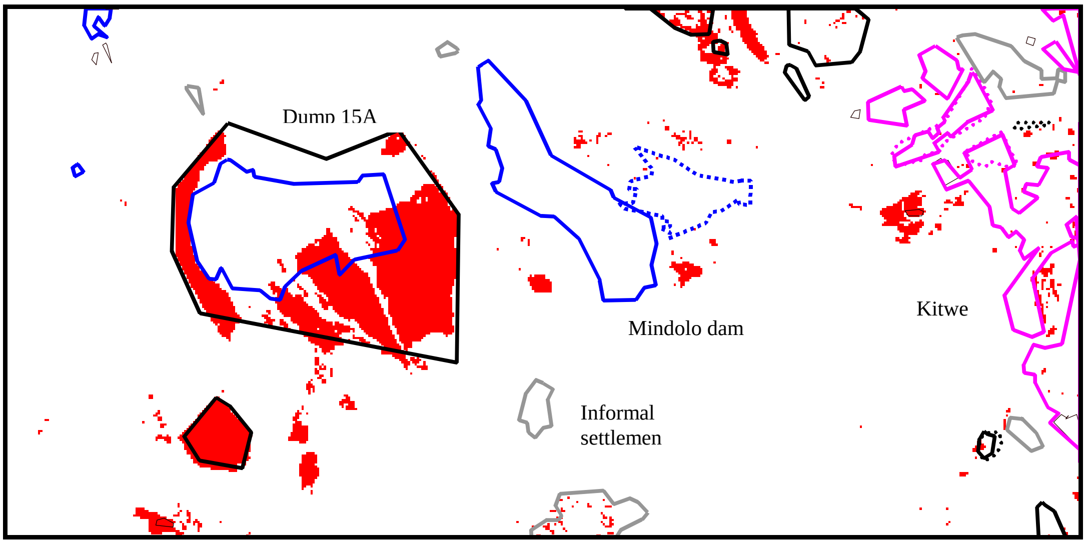

Figure 4. **A change map of the Mindolo area showing classified 1997 Landsat data in red with map data shown as polygons. Dashed lines refer to data from 1968 aerial photography and solid lines refer to 1984 photography. Grey: informal settlements, magenta: urban areas, blue: water bodies and black: tailings deposits.**

6. CONCLUSION

From the analysis of spatial data, it is apparent that land use in the Mindolo area has changed significantly over the last three decades. The total area of land occupied for urban land use and for the storage of mine residues has increased by at least 1 189 ha (6 fold).

Mine data provides insight into the effect of the tailings deposits on water quality. The potential salt and metal loading on the surface streams at Mindolo dam has increased with each increase in surface area of the dump, increasing the strain on a stressed environment. Increasing population pressures will lead to greater utilization of resources such as land and surface water contaminated by tailings. The current operational state of Kitwe's water purification equipment and the large number of informal settlers, who use unpurified water, will lead to a greater risk of poisoning. The dump 15A/Mindolo dam complex is thus a critical area for the application of environmental management.

To make full use of the satellite data, more sophisticated image processing is required. Proper delineation of the stream catchment using a digital elevation model would further improve the quantification of impacts. The next stage in this investigation includes the integration of chemical speciation models into the GIS to trace alterations in water chemistry along the water courses. Atmospheric dispersion models will permit quantification of the impact of dust from dumps like 15A on surrounding land and should be included in future studies.

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