# ASSESSMENT OF MINING INDUCED ENVIRONMENTAL DEGRADATION USING SATELLITE DATA AND PREDICTIVE MODELS

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## ABSTRACT

*Kitwe is the largest city on the Zambian Copperbelt. Copper has been exploited around Kitwe for more than seventy years with severe environmental consequences.*

*Tailings impoundments and a large metallurgical facility located near Kitwe are suspected of causing surface water and groundwater pollution. Several installations are located in sensitive headwaters. One such tailings impoundment is Dump 15A, runoff from which flows into the Mwambashi River, where water is abstracted for agriculture and for domestic consumption in Kitwe. The Mwambashi is a tributary of the Kafue River on which more than 40% of the Zambian population depend for water. The quality of this water is therefore critical to the general health of the Zambian populace. Fatal poisoning of livestock has been reported along the banks of the Mwambashi river (Mwale, 1996).*

*To assess the impact on the water environment, a study of the spatial distribution of environmental aspects has been undertaken using a GIS. The results of this GIS analysis are combined with geochemical modelling to determine the characteristics of surface waters and how these change over time and space.*

*Data acquired by Landsat TM, land cover data derived from maps, water quality data and the results of water quality modelling can be combined to present a comprehensive picture of water quality alteration due to mine installations and their impact on the Mwambashi and Kafue rivers. Difficulties associated with this approach include the absence of historical surface water data and the low density of sampling points in the area of interest.*

## 1. INTRODUCTION

### *1.1 Mining in the Kitwe Area of the Zambia Copperbelt*

Mining has been conducted near Kitwe for over seventy years. The long history of mining and the presence of other sources of pollution complicate assessment of environmental impact in Kitwe and it is thus desirable to select an appropriate indicator of environmental change. During this period, vast amounts of mine residue have been produced and disposed of on surface. These residues, consisting of broken rock, fine particles and slag, provide an indication of the extent of mining and are therefore indicators of environmental impact. Assessing changes in these residue deposits over time provides insight into the changing stresses on the environment.

Both the slag and fine particles (tailings) contain metals in various concentrations. The tailings impoundments are particularly susceptible to both fluvial and aeolian erosion. This natural degradation of tailings impoundments represents a prominent source of metals in the environment (Baudo, 1987). Furthermore, pollutants derived from tailings are persistent and remain in the system to become available again with the onset of favourable conditions (Baudo, 1987).

The largest tailings impoundment in the Nkana Division of Zambia Consolidated Copper Mines (ZCCM), Dump 15A was commissioned in 1971 near Mindola Dam, outside Kitwe. This impoundment, sited over a former wetland, contained 70 000 000 tonnes of tailings by 1996. Between 1988 and 1996, 20 158 800 t of material was emplaced at dump 15A through various pipelines. The average emplacement rate during this period was 255 175 t of tailings per month at an average concentration of 0.1% copper and 0.03% cobalt (ZCCM, 1996). The impact of this impoundment on the surrounding environment is poorly understood.

## *1.2 Water and Mineral Pollution*

Flowing water is the dominant agent in landscape evolution. Sediment transportation by rivers is effected by a complex combination of processes, including suspension, deposition, erosion and redeposition of the sediment as alluvium. The alluvial matrix is continually enriched by deposition, adsorption and precipitation processes, explaining both the enhanced fertility of river basins relative to uplands and their increased susceptibility to contamination (Davies, 1987).

Many tailings impoundments are a significant source of contamination in a mining landscape by virtue of their large volume and fine particle composition. Through natural grading of the sediment load in rivers fine particles are transported the farthest. Such particles usually contain higher amounts of sorbed chemicals and thus chemical enrichment in eroded sediments is an important contaminant transport medium in mining areas (Ghadiri & Rose, 1992).

Baudo (1987) states that the heavy metals most frequently reported as pollutants are cadmium, copper, mercury, lead and zinc, the fate of which is largely dependent on the heterogeneous equilibrium established between dissolved and suspended compounds. Notwithstanding this observation, sediments act as a sink for most pollutants (Baudo, 1987). The only reported occurrence of chronic copper poisoning in the Kitwe area occurred through the ingestion of contaminated sediments deposited on the banks of the Mwambashi River. In 1981 chronic copper poisoning of livestock, resulting in the death of cattle, sheep and goats occurred, on farms adjacent to the Mwambashi (Mwale, 1996). Copper was present in the river sediments and in riverside vegetation with concentrations of the metal ranging from 3 000 μg/g to 20 000 μg/g in the river sediments (Brasser & Charman, 1982 in Mwale, 1996). It is therefore important to identify downstream areas on a river's floodplain that are susceptible to sediment deposition.

## 2. ENVIRONMENTAL IMPACT

### 2.1 Sampling

Chemical data used in this investigation are derived from two sources: a field trip made to the area of interest (AOI) by the author and an environmental impact scan of the mining lease conducted on behalf of the mine by consulting engineers. The number of sample sites is sub-optimal and gaps are present in the data, especially in groundwater samples. Despite this, interpolation of sample values provides insight into the spatial variation of water quality within the AOI.

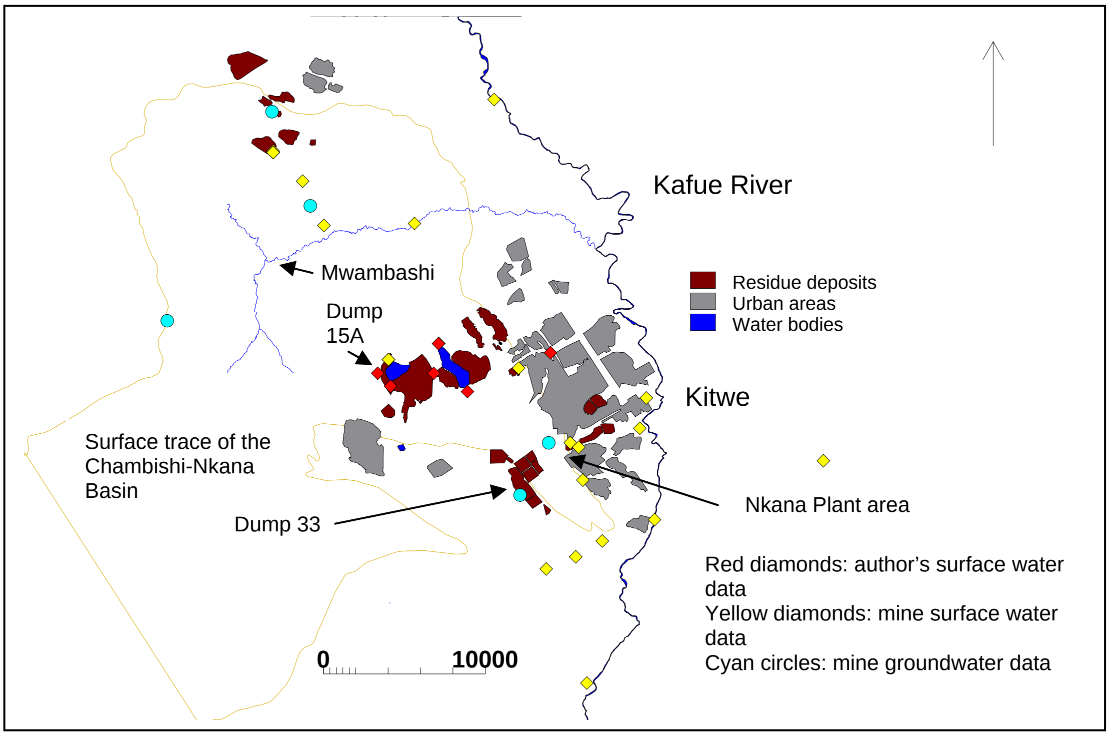

**Figure 1.** The area of interest showing the city of Kitwe, the Kafue River, mine waste disposal facilities and sample sites. Geology digitised from *Geological Map of Chambishi Basin and Katembula, Chisanga and Chiryongoli Domes*, RCM Geological Services, 1: 125 000, 1981.

Land use classes identified in figure 1 are derived from classification of 1998 Landsat Thematic Mapper (TM) data using aerial photographs to verify classifications. Dumps and water bodies were delineated using a normalised difference vegetation index. This shows hard anthropogenic surfaces and water bodies, both of which are free of vegetation, as dark patches in the image. Areas with high vegetation density are bright.

### 2.2 The Kafue River

This river receives mine effluent from most of the Zambian Copperbelt. All of Nkana Division's surface runoff finally ends up in the Kafue. Two sites provide insight into the changes in the river as it passes Kitwe.

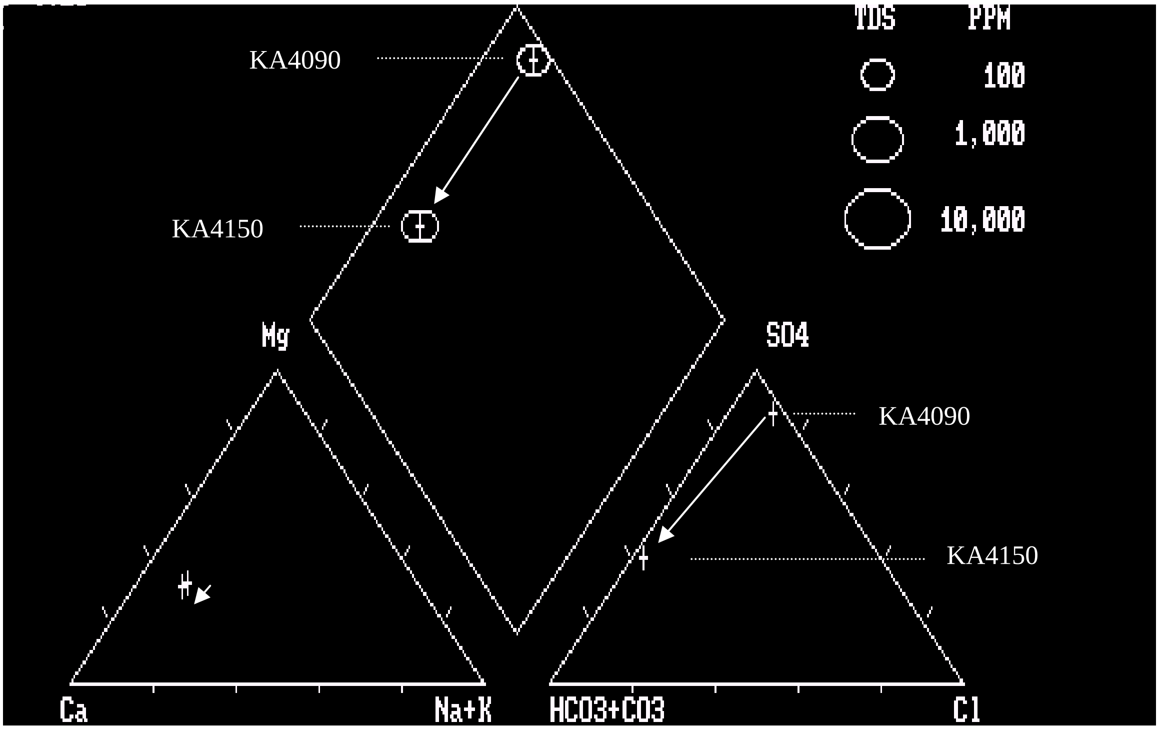

**Figure 2.** Piper diagram showing changes in the chemistry of Kafue waters as the river passes through the AOI. KA4090 is a sample site approximately 18 km north of Kitwe and KA4150 lies 10 km to the south of the city. . Plot produced in WATEVAL.

In figure 2, water in the Kafue above Kitwe plots near the upper apex of the Piper diamond. This implies water rich in both $Cl^- + SO_4^{2+}$ and $Ca^{2+} + Mg^{2+}$. The water has permanent hardness. After it's passage downstream though the Nkana lease area, the water is characterised by temporary hardness, rich in $Ca^{2+} + Mg^{2+}$ and $HCO_3^-$. The TDS concentration in the Kafue water increases as the river flows past Kitwe. The changes shown in the lower triangles of the Piper plot indicate calcite solution (Hounslow, 1995). TDS in river water over this stretch increase from 152 mg/l to 200 mg/l. This is to be expected as several installations in the Nkana lease area show high surface water calcium contamination. Of these dumps 15A and 33 as well as the plant area show prominent calcium enrichment of surface water. A groundwater sample collected near Dump 33 shows calcium enrichment which is absent from the Nkana Plant area groundwater sample. No analysis of groundwater is available for Dump 15A area and this has influenced the interpolation of sample values, probably resulting in an underestimation of contamination at 15A. Calcium enrichment is, however, clearly associated with mine installations in the AOI.

### *2.3 The Mwambashi River*

This river drains the Chambishi-Nkana Basin – the geological structure that hosts the copper deposits within the AOI. The Mwambashi receives runoff from Chambishi Mine north of Kitwe and from the large tailings facilities of Nchanga Division. Water from Nchanga reaches the Mwambashi via the Muntimpa Stream. Other investigators (Berglin, 1997, Hedström & Osterman, 1996) have concentrated on the impact of the Nchanga on the Mwambashi and a detailed assessment of the river will not be presented here. Runoff from Dump 15A via a tributary of the Mwambashi is considered in detail.

## 3. MODELLING

### *3.1 The Digital Elevation Model*

The modelling of pollutants in overland flow is impossible without accurate representation of runoff (Ghadiri & Rose, 1992). Consequently, representing the hydrologic behaviour of a catchment is important. The process of sediment loss provides the major transport mechanism for all sorbed pollutants and the interaction of pollutants with sediment loss and runoff results in the overall transport of these non-point source pollutants (Ghadiri & Rose, 1992).

Topography has a significant influence on the response of a catchment to rainfall. It also has a significant effect on the ecological dynamics of the landscape (Moore *et al.*, 1993). In a GIS environment, the topographic attributes of a landscape may be quantified using digital elevation models (DEMs) which determine:

- the path followed by contaminated surface water flowing away from a tailings installation and
- the area potentially affected by the pollution plume associated with this water.

In this investigation, a 9 x 9 moving window has been used to produce streamlines with reference to a DEM which has been pre-processed to remove pits. The DEM was generated by interpolation of 50 foot (15.2 m) contour lines present on 1:50 000 government topographical maps of the area: 1228C1 Mufulira West, 1228C2 Mufulira East, 1228C3 Kitwe and 1228C4 Mabote. By the Peuker criterion, a DEM grid size has to be 4.3 times the contour interval of the source map (Sasowsky et al., 1992 in Florinsky, 1998). Accordingly, the grid size used here is 65 m. DEMs generated with 25 m grids contained a large number of artefacts and were discarded. The accuracy of the source maps is questionable. Difficulty has been experienced in registering satellite images to these maps and a large number of pits and flat areas were created in the DEM during interpolation. As is often the case, no alternative datasets were available and therefore the study proceeded with a DEM generated from these maps.

An area for detailed examination was defined as a submap of the 50 x 50 km area represented by the four toposheets. This submap is approximately centred on Kitwe, approximately 30 km wide, extending from the Mwambashi River in the north to about 10 km south of the city centre.

The logic statement used to remove pits in the DEM was run in the GIS software ILWIS 2.2:

```
iff(mindflat,mindem,iff(minsub1=1,iff(nbminp(mindem#)=5,nbsum(mindem#)/9,mindem),mindem))
```

where: mindflat is map showing flat areas on the DEM
minsub is map defining the boundaries of the DEM (to avoid artefacts)
mindem is the original DEM
nbminp and nbsum are neighbourhood operators; nbminp returns the neighbour with the lowest value and nbsum returns the sum of the neighbouring pixel values for each pixel

Mindflat was generated using the following expression:

```
nbcnt8(mindem#=mindem)=8
```

where: nbcnt is a neighbourhood operator which tests the number of neighbours
which satisfy a specified condition, in this case 8 neighbours which
have the same elevation as the central pixel

The modified DEM was use to propagate streamlines from waste sites to the nearest major river. These sites were identified using Landsat TM colour composite maps. The propagation was stopped at the rivers as the Kafue and it's tributary, the Mwambashi, both transport pollution from other mining lease areas. This makes chemical contouring of water from the AOI difficult to interpret.

The streamline propagation expression was constructed as follows:

```
iff(mintg15,mintg15,nbmax8(mintg15#,mindir#=nbpos))
```

where: mintg is a raster map containing target pixels from which the propagation
starts
mindir is a direction map derived from the DEM
nbmax8 is a neighbourhood operator that returns the highest neighbouring
value for each pixel

This expression was run through an iterative sub-routine until no further changes were made to the map.

Scanned, georeferenced aerial photographs of the AOI were used to locate decant structures and drainage channels associated with the tailings impoundments. Two seepage/failure zones where also identified in the south of the AOI and flagged as starting pixels for stream propagation.

Once the streamline propagation was complete, pollution plumes associated with each streamline were generated to identify areas liable to contamination by waterborne pollution from each source.

```
iff(mintg15,mintg15,nbmax(mintg15#,mindem#>mindem))
```

In the streamline propagation statement, only the lowest pixel is recoded while in the plume propagation statement, all pixels that occur at an elevation lower than a flagged pixel are recoded. This results in a relief-controlled spreading of the propagation with distance from the target.

The DEM modelling was undertaken to provide a spatial framework for geochemical assessment of water quality in the AOI. Several water quality data sets were collected in AOI by the mine and by the author. These were assessed for completeness and then used to characterise the chemical environment of the AOI.

### *3.2 Surface Water*

Samples collected across the AOI were loaded into ILWIS after checking anion/cation balances in WATEVAL, a water quality evaluation program written by A.W. Hounslow and K.D. Goff (q.v. Hounslow, 1995). Most analyses were found to have a balance of around 10%, which while high, is adequate for the purposes of this study.

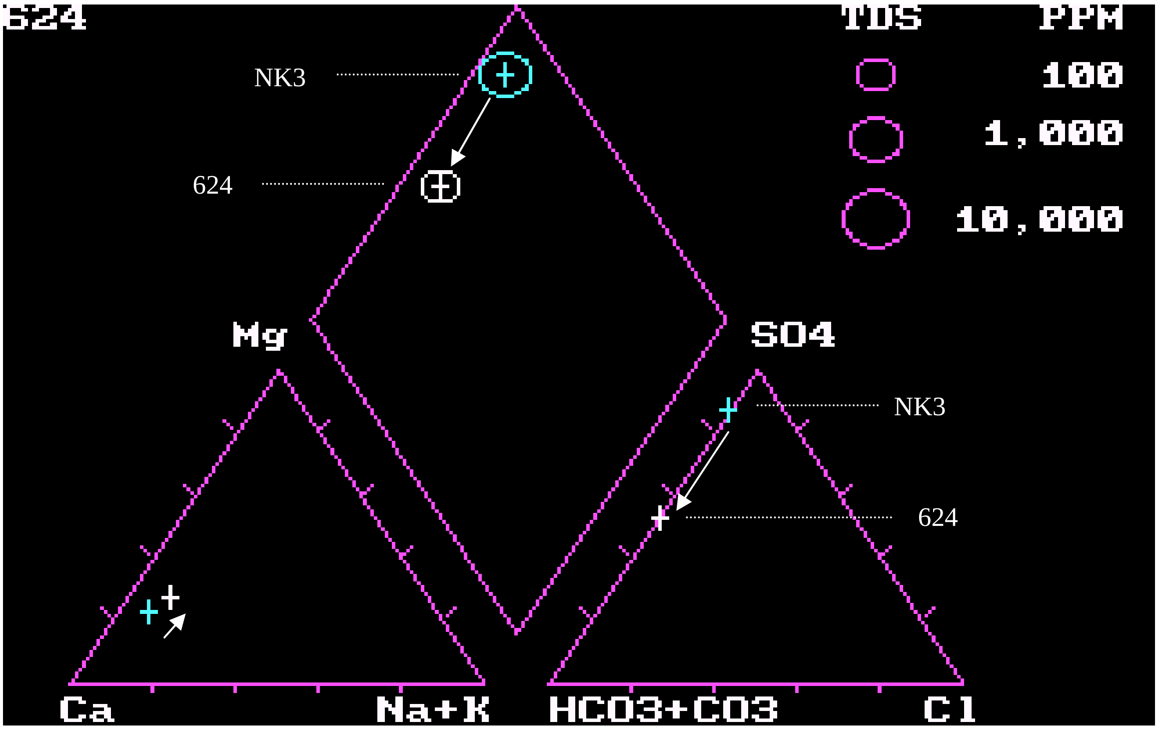

**Figure 3.** Changes in water chemistry in the surface stream from the dyke failure at tailings dam 33 (site NK3) downstream to sample site 624, before the confluence with the Kafue. Plot produced in WATEVAL.

This Piper plot shows a natural amelioration of process water-derived contaminants with distance downstream. TDS decrease, calcium concentration decreases slightly and sulphate concentration decreases dramatically.

In ILWIS, planar moving surface interpolation was performed on point maps with X-Y positions defined by sample sites and values defined by analyses for the determinand in question. The resulting maps showed a continuum of water quality values across the AOI. This is an unrealistic representation of surface water. The interpolated value maps were crossed with the plume maps to produce surface water values constrained by the spatial extent of the plumes.

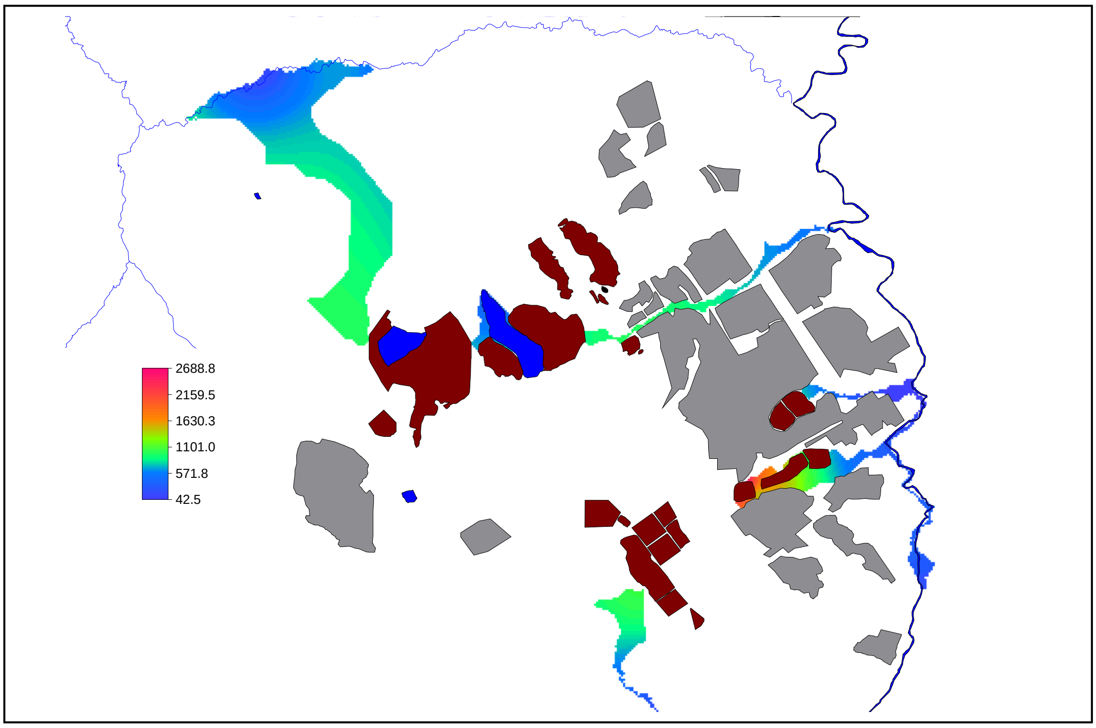

**Figure 4.** Spatial variation of $SO_4$ concentration (mg/l) in identified surface water pollution plumes.

From the sulphate map above, it is clear that areas with high sulphate concentrations overlap with urban land uses in several instances. The flatter topography in the north of the map results in runoff from Dump 15A affecting a larger area that that from the older dumps draining towards the east and south. The highest sulphate concentrations in the AOI occur in the waters draining the Nkana Plant area.

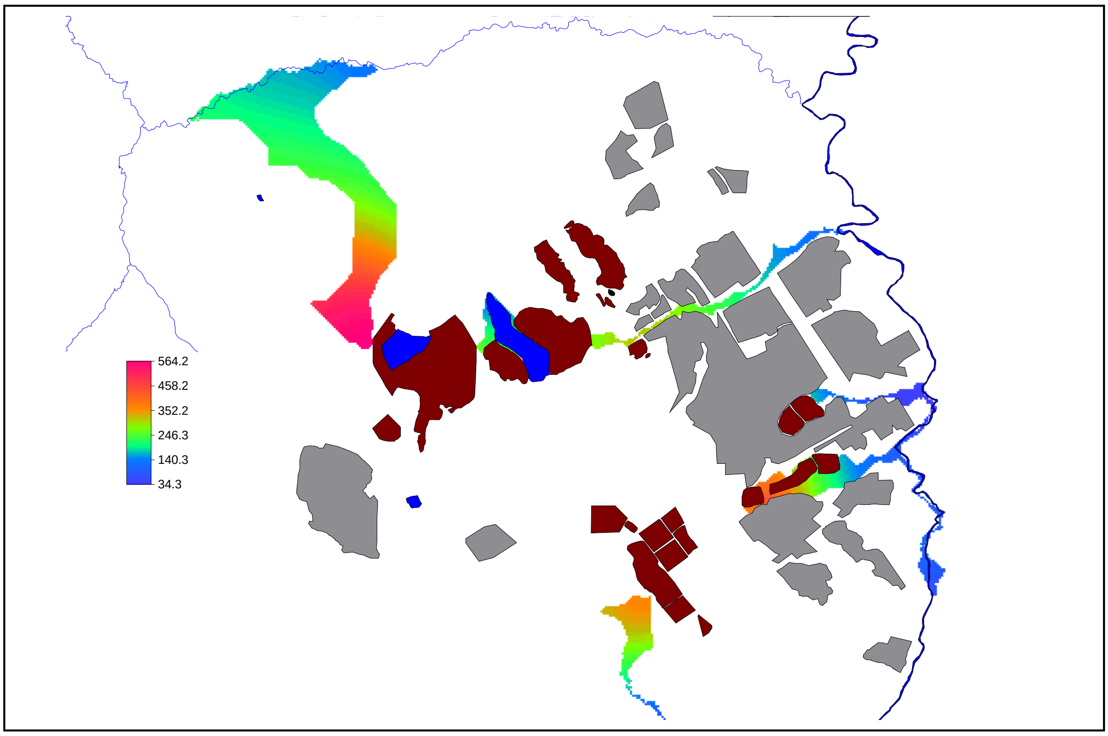

**Figure 5.** Ca concentration (mg/l) in surface waters.

The use of a DEM has shown that surface water from the Mindola dam is unlikely to flow to the Ichimpe Stream as has previously been reported (Limpitlaw, 1998). This stream is an important hydrological conduit as may connect a pollution source with a drinking water abstraction station. The streamlines predicted by the DEM employed here will be verified through the generation of another model from different data.

High calcium concentrations are associated with operational tailings disposal facilities. This is expected as liming is undertaken for pH control. Copper concentrations in surface water peak in the drainage from the plant as with sulphate. Iron exhibits an interesting distribution as the highest values (360 mg/l) are found east of the Kafue River over granite rocks with no mining or mineralisation present.

### *3.3 Groundwater*

Groundwater samples were collected by the mine and represent samples of water taken from below the soil horizon. The mineralised strata in the AOI occur within the sediments of the Katanga System. These rocks lie unconformably on crystalline basement granites and gniesses. Within the AOI, the Katanga sediments occur within the Chambishi-Nkana Basin, the boundary of which is shown in figure 1. Some strata within this basin, such as the dolomites of the Upper Roan, are known aquifers and therefore treating the area as a homogenous groundwater surface is questionable. Attempts at interpolating samples within the basin separately from those occurring outside of the basin yielded poor results due to insufficient sampling density. For this reason, maps are presented which depict free flow of groundwater across the basin boundary.

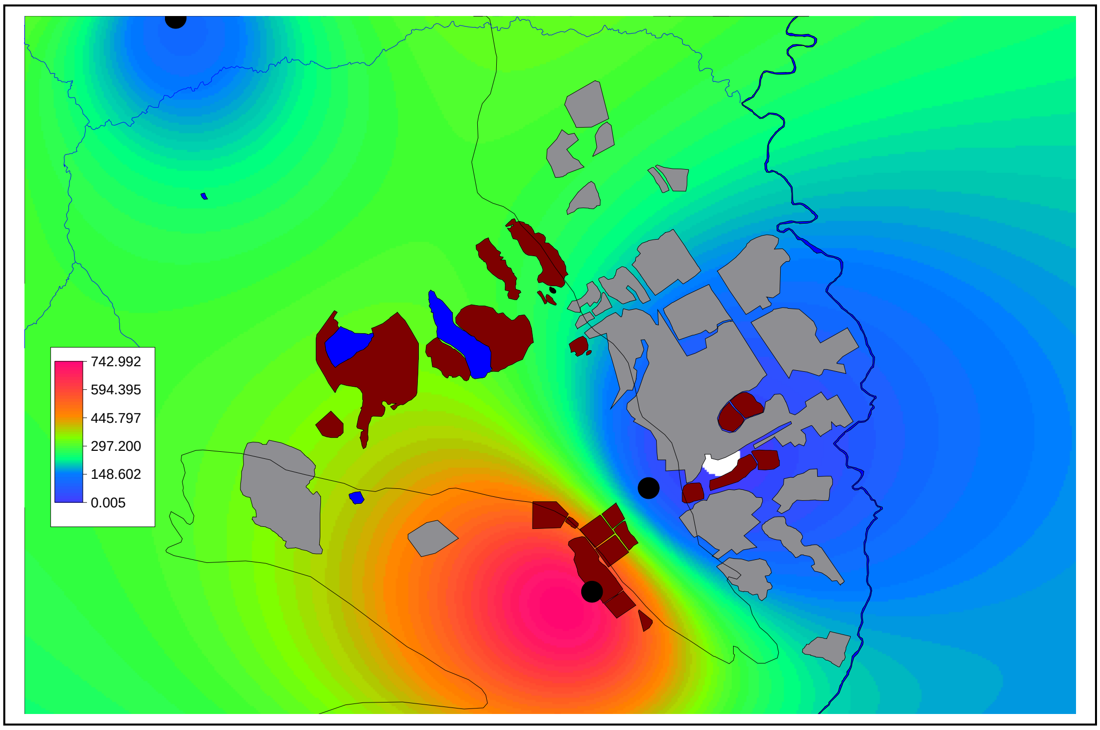

**Figure 6.** Groundwater Ca concentrations interpolated assuming homogeneous geology. The white area adjacent to the old tailings impoundment is of undefined Ca concentration value due to insufficient sampling points.

High calcium concentrations in groundwater are associated with tailings facilities as is the case with surface water. The lack of a sample point near Dump 15A severely reduces the value of this dataset as contamination of the groundwater near this facility is most likely.

Groundwater sulphate concentrations with the AOI are generally low compared to sites located in other lease areas. There is a general west-east decrease in sulphate concentrations. Groundwater alkalinity (as mg/l $CaCO_3$) exhibit the inverse trend as is to be expected. Metals such as iron and copper have the highest concentrations in the north of the AOI near Chambishi Mine and exhibit a west-east trend similar to sulphate over the rest of the AOI.

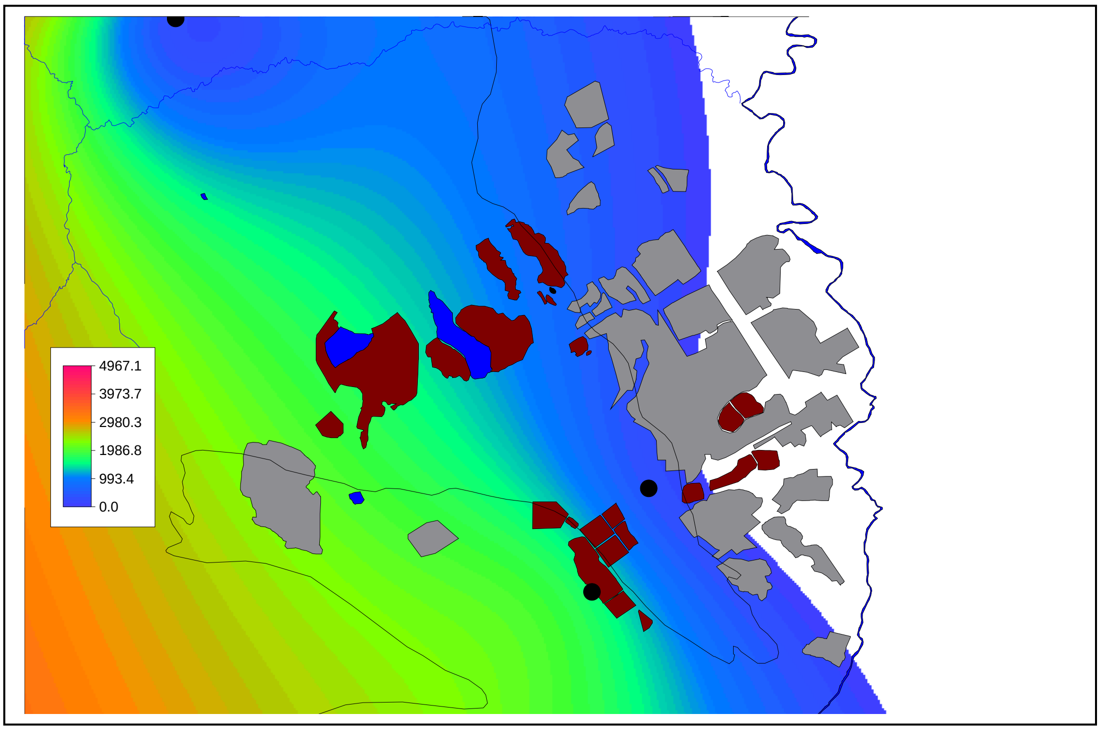

**Figure 7.** Groundwater $SO_4$ concentrations interpolated assuming a homogeneous geology. Black circles represent sampling sites; white the area has undefined $SO_4$ concentration due to insufficient sampling sites.

## CONCLUSION

Elevation modelling indicates that surface flow from Mindola Dam north overflow to the Ichimpe stream is unlikely due to intervening relief. If Mindola water is reaching the Ichimpe, then ground water flow must play an important role. This is a potentially important pathway for present and future contamination of Kitwe's water supply and must be investigated further.

Pollution arising from old, ring-dyke tailings dams south of Kitwe is significant and is as important as that arising from Dump 15A.

This study has provided a basis for future investigations. An important aspect not quantified in this investigation is surface runoff volumes. Historical rainfall data is available and will be used in a hydrological model to estimate mass loadings of pollutants in each of the catchment areas identified here.

Together with runoff, sediment transport through the AOI landscape must be investigated as this is likely to be a significant vector for pollution transport.

The concurrent use of GIS and chemical models allows visualisation of data, highlighting data gaps and spatial trends. These can be interpreted with the aid of chemical trends in the data.

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