An example of GIS use in surface and ground-water pollution sensitivity analysis: Regional impact of mining activities in South Africa

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Abstract

South Africa, a major mining country, suffers dramatic environmental problems related to mining activities, particularly soil water pollution by sediments and water from the gold extraction plants and tailings dams. BRGM and the Council for Geoscience have undertaken a joint research project into the use of Geographic Information Systems for assessing the environmental impact of mining.

The pilot study area covers a portion of the West Rand that suffers significant environmental impact (radioactive and acid mine drainage) due to the mining and processing of ore from the Witwatersrand Supergroup.

The methodology presented here intends to develop a GIS-based tool for assessing the environmental impact of mining at a regional scale. It is based on the integration and thematic processing into a GIS of several data with different origins and topologies (geology, airborne geophysics, satellite imagery, Digital Elevation Model, data on surface and groundwater quality).

To date, the research has achieved the following :

- development of qualitative risk-based methodology for soil and water pollution-sensitivity analysis as well as for groundwater vulnerability. This methodology is of use as a guide to future development and the identification of critical problems areas.

- identification of surface areas polluted by mining activities, which may also contaminate groundwater.

identification of surface run-off pollution dispersal pathways from the tailings dams and their connection with potential infiltration zones.

The addition of reliable data on groundwater aquifers will also allow the evaluation of the dispersal of pollutants in groundwater from infiltration points on the surface. These points will combine known areas of infiltration and areas identified in this study.

The techniques developed may be used to develop a GIS-based decision tool that allows an assessment of the impact of mining activities at present and be used in the implementation of future mining and related developments. Furthermore, the application of these tools in other environmental scenarios is envisaged.

1. Introduction

For more than a century gold has been mined in the Witwatersrand Basin. During this period, little attention has been paid to the environmental impacts of this mining. The gold ores of the Witwatersrand contain appreciable concentrations of pyrite and uranium and other metals, which has led to the contamination of the environment with salts, metals and radionuclides (Kempster *et al.*, 1996). This study looks at a portion of the West Rand Goldfield (See Fig. 1).

The pollution of ground and surface water by mining activities in the Witwatersrand poses a serious and quantifiable threat to current and future generations, especially in the context of the scarcity of water in South Africa. More research needs to be focused on this problem and research needs to be carried out at catchment and aquifer scale, rather than the current mine-scale research, which tends to view individual mines. Geophysical methods and remote sensing, which are able to cover large areas rapidly in a cost-effective manner should be applied.

An important approach to the problem is the application of Geographical Information System (GIS) based risk-assessment methods. If the risk of contamination and threat posed to people and the environment can be adequately assessed, it allows for the assessment of the seriousness of problems, prioritisation of remedial actions and the prediction of future problems, as part of the planning process. A new methodology and the results of its application is presented in this paper.

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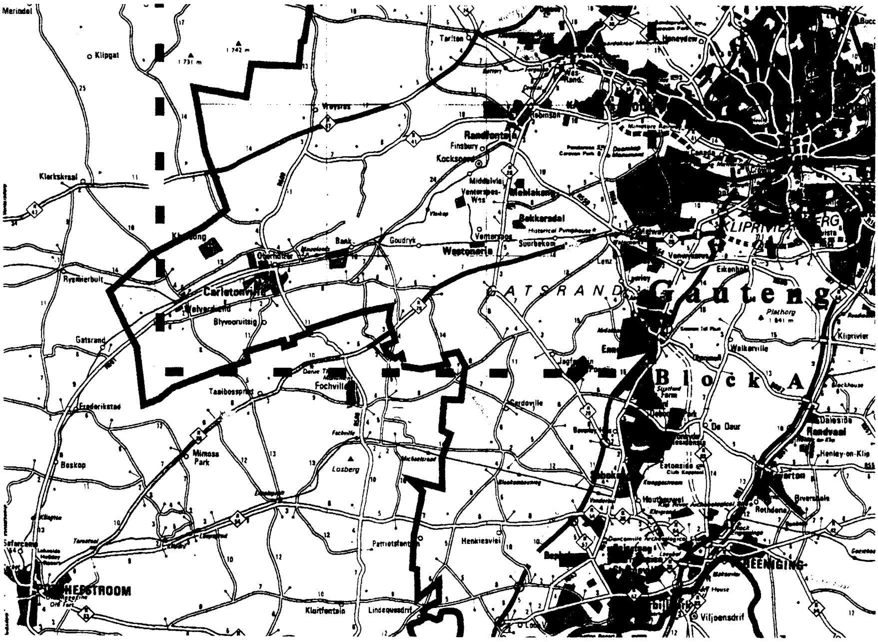

Figure 1. Location of the pilot study area (indicated by dashed line) in Gauteng Province, South Africa.

2. Environmental and Geological conditions in the pilot study area

2.1. Environmental considerations

The presence of a number of tailings dams, waste rock dumps, other waste deposits and tailings spills in the area allows pollutants to enter into the environment. Different pollution paths have been identified, including :

- Direct pollution of surface-water and air by mine wastes
- Soil contamination
- Underground water pollution through :
  - Direct infiltration from tailings dams
  - Deliberate dumping of tailings as fill material into sinkholes
  - Indirect downstream infiltration through drainage systems collecting polluted surface water and sediment.

This provides guidelines for the development of a GIS model for assessing the environmental impact of mining at a regional scale. The model must be able to assess :

- the pollution sources
- the contaminated surface areas
- the surface run-off pollution dispersal pathways
- the groundwater vulnerability, *i.e.* potential communication from surface to groundwater.

2.2 Geological Context

The study area is underlain by a succession of rocks from Archaean granites and greenstone remnants through sediments and lavas from the early Proterozoic Witwatersrand and Ventersdorp Supergroups to the younger Proterozoic Transvaal Sequence. This succession is exposed on the limbs of the east-west trending Rand Anticline, which bisects the area. Localised inliers of Permian Karoo sediments are found in places. A number of dykes, sills and other intrusions are also present.

The dominant geology of the mining areas are Witwatersrand sediments in the Krugersdorp-Randfontein area, and dolomite of the Malmani Group, with the southernmost mines being developed on the Pretoria Group both of the Transvaal Sequence. All of the mines extract ore from the Witwatersrand rocks. The area can therefore be classified into two main natural hydrogeological regimes, the weathered and fractured aquifers of the Witwatersrand and Pretoria sediments and the solution channels of the dolomite. In addition, shallow mining in the Krugersdorp-Randfontein area has produced am "artificial aquifer", water moving through old mine workings. The dolomitic aquifers are of great importance, as they form a potentially significant source of water for industrialised Gauteng, the most populous province of South Africa.

Since the onset of mining, and especially since the early 1960s, some of the dolomitic compartments have been dewatered, to allow mining to proceed safely below the dolomite (Jordaan *et al.*, 1960) In areas where karst and palaeokarst features exist, this has led to the formation of sinkholes and other subsidence features. Due to the proximity to the mines and the good drainage, most tailings dams have been developed on dolomite. This provides a direct infiltration pathway into the groundwater, where sinkholes and other solution cavity features provide direct contamination pathways under the tailings dams.

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3. The GIS Model

3.1. Raw Data

With respect to the proposed GIS model , the following data have been introduced into the data base :

- a geological map: an image derived from the Council for Geoscience's digital 1:250 000 scale coverage
- airborne geophysics: images of magnetic and radiometric (K, U, Th and total count) data
- surface and groundwater analyses and water table depths (point data provided by the Department of Water Affairs and Forestry)
- satellite imagery : SPOT and Landsat Thematic Mapper images
- high resolution digital elevation model (DEM) derived from a SPOT stereo pair
- low resolution digital elevation model (DEM), supplied by the South African Trigonometric Survey.

3.3. Identification of areas with pollution at surface

As a result of the high uranium contents in the ores, all the waste streams show radioactivity values significantly elevated above local natural background values. A further diagnostic property of the ores and their wastes is a significant deviation from natural U/Th ratios. In most naturally occurring rocks this ratio is of the order of 0.1 to 0.5. The ore materials however are enriched in uranium, having U/Th ratios generally greater than 1.

Since 1991, the Council for Geoscience has undertaken high-resolution radiometric surveys over parts of the Witwatersrand Goldfield. These have provided valuable data defining the nature and extent of radioactive pollution of the surface material (Coetzee & Szczesniak, 1993).

Two diagnostic tools have proved extremely successful in the identification of pollution. RGB composite images of the potassium, uranium and thorium channel radiometric data have proved excellent in locating such areas with anomalous radioelement ratios. A simpler, but equally effective method was applied using the U/Th ratio as a diagnostic ratio, and reclassifying an image of this ratio to identify all areas with U/Th>1 (see Fig. 2). This allows the interpreter to discern areas with the characteristic high U/Th signature of mine waste and produces a map of surface pollution.

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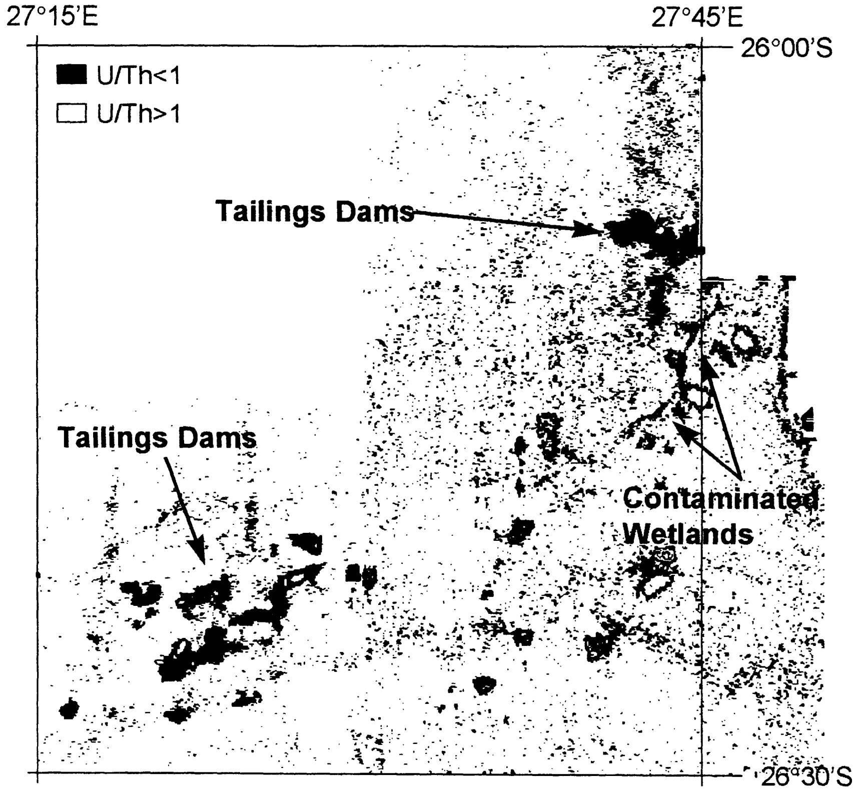

Figure 2. Airborne-radiometric image of the U/Th ratio showing radioactive contamination sources (tailings dams) and contaminated surroundings and downstream wetlands.

Furthermore, image overlays between airborne radiometric data and high resolution remotely sensed data provide an invaluable interpretative tool. The combination of total count radiometric data or of U/Th ratio image with one of the visible spectrum bands of SPOT multispectral satellite remote sensed data allows direct identification of ground features emitting radiation and the dispersal of pollution into the environment, particularly visible in the wetlands downstream of the sources.

It is also important to note that this method may be applied with the radioactivity viewed as a diagnostic property of the waste streams. The wastes include a large number of other contaminants, including toxic heavy metals, and the leakage of these into the environment may be predicted, using the airborne radiometric data to locate leakage. It is however important to remember that radiometric data indicates the activity of radionuclides at the surface in soil or rock, but will not indicate contaminated water directly.

3.2. Identification of surface pollution dispersal pathways

3.2.1. Derivation of drainage from digital elevation models

The airborne radiometric data clearly show the downstream movement of contaminants along surface channels. The model must therefore consider dispersal of pollutants by surface run-off as well as the direct infiltration into groundwater. The transported pollutants can then enter the groundwater through karst or other features downstream. Modelling these dispersal pathways therefore forms an essential part of regional assessment of pollution.

It is possible to model the run-off of water from point and area pollution sources, using a number of automated algorithms. This has been applied to the tailings dams in the study area, to produce a pollution run-off map, indicating all channels which accept flow from polluted source areas. (See Fig. 3). It is also clear that most of the pollution from the mines in the study area gathers into the Wonderfonteinspruit. This river is currently the subject of an intensive study into high levels of radioactivity and carries an elevated sulphate load. Wetlands along the Wonderfonteinspruit also contain anomalous levels of radionuclides from the ^{238}U decay series (See Fig. 2).

The contaminated flow coverage can be combined with a total flow coverage to produce a map showing the general contamination patterns and pathways in a regional context. For the study area, this highlights the contamination of the Wonderfonteinspruit and its tributaries, which flow through the towns of Carletonville and Welverdiend and downstream towards Potchefstroom, a major local population centre.

It is also possible to isolate contaminated drainage which passes within a specified distance of a known infiltration point and to relate this drainage to a specific tailings dam or other pollution source. Such points could include sinkholes, dolines and other karst and palaeokarst features.

3.2.2. Comments on the quality of digital elevation models

Such modelling however requires high quality digital elevation models. The initial part of this study was undertaken on a subset of the area covered high resolution DEM produced from a SPOT stereo pair. Extension of this the study area required the use of a lower resolution DEM obtained from the South African Trigonometric Survey. The pathways predicted from this DEM are not as accurate as those from the satellite derived DEM, showing small deviations from channels in flatter areas.

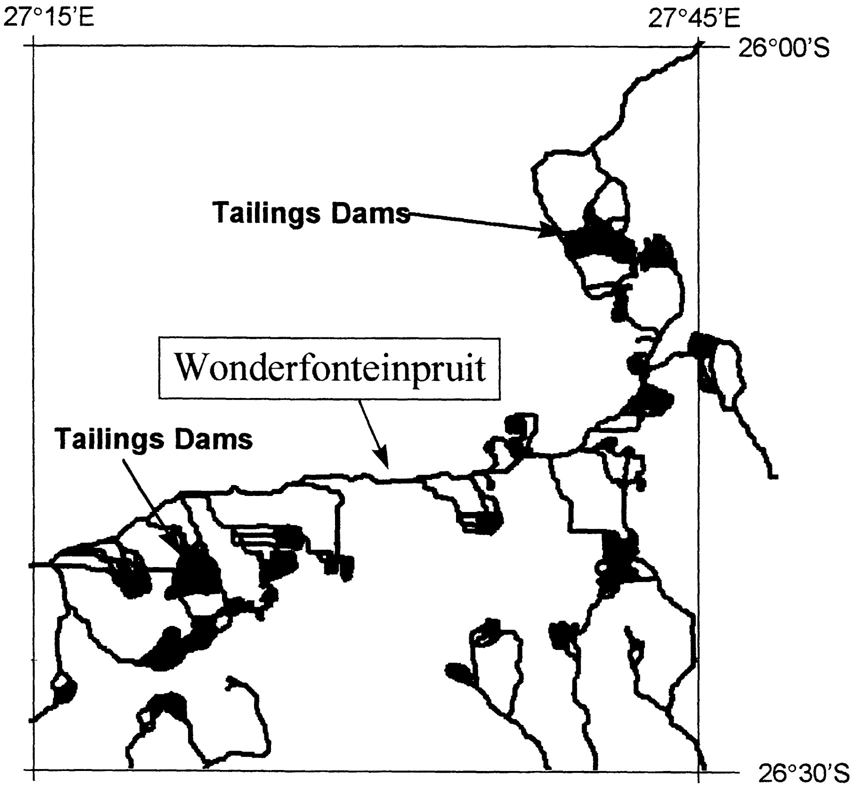

Figure 3. Run-off pollution dispersal pathways from tailings dams

3.3. Verification of surface pollution patterns

The two methodologies described above produce two coverages of surface pollution. The first is based on measured soil and ground contamination, while the second attempts to locate the pollution pathways. Comparison of these two images shows a good correlation between surface contamination and modelled contamination run-off paths. Furthermore, water analyses with elevated chemical and radioactive pollutants are generally located in areas with elevated U/Th ratios and contaminated flow.

3.4. Groundwater vulnerability assessment

The aim of this assessment is to identify areas where the groundwater is at risk of contamination by the direct vertical infiltration of contaminants from the surface. This problem can be approached using qualitative and quantitative techniques, however the limited data and regional character of many of the datasets preclude detailed quantitative modelling, but are adequate for the purpose of producing a regional risk-assessment. It must be stressed however that a full risk assessment will necessarily involve the capturing and measurement of additional data.

With respect to data availability, several levels of assessment can be performed. At the most basic level, simple boolean decision rules have been applied to the GIS coverages described in the preceding paragraphs. This allows the analyst to answer specific questions based on *a priori* information regarding the study area. This approach necessarily includes the bias of the analysts, but is able to rapidly identify areas of high vulnerability to pollution. In addition, the approach is well suited to areas where reliable data are not readily available or all the parameters needed for quantitative analysis.

As more data become available, more quantitative models of groundwater vulnerability, such as the calculation of DRASTIC groundwater vulnerability indices model (Aller *et al.*, 1987, cited by Lynch *et al.*, 1994) may be used. This method has been applied, using some assumptions described by Lynch *et al.* (*op. cit.*) specific to Southern Africa. If all the required data are available, quantitative models may also be applied.

Both of the approaches described above are ideally suited to raster GIS analysis, as the algebraic or boolean equations can be used to combine raster images to produce a single image of groundwater vulnerability.

The third approach is to use a GIS decision support, and to develop a weighting system for the parameters used algorithm (BRGM, 1997, Eastman *et al.*, 1995). This can then be applied and the results tested against specified criteria and constraints. The results of these assessments are then used in the simulation of the siting of a new tailings dam.

4. Simulation of the siting of a new tailings dam

The final phase of the study has been applying the available data to a simulation of the development of a new tailings dam. Here again, a number of criteria need to be included in the evaluation. In this study a simplified set of criteria have been applied in an attempt to locate the site most suitable for the development of a new tailings dam. Two competing considerations have been taken into account:

- The tailings are wet when dumped, and the dam needs to be able to drain adequately if it is to maintain its structural integrity
- The leachate, draining through the tailings can become highly contaminated and poses a serious threat to ground and surface water in the area.

The site selected for a new tailings impoundment must therefore lie in an area of low groundwater vulnerability, with sufficient gradient to allow good surface drainage. At the same time, the area should not be prone to flooding, as inflowing stormwater can compromise the structure of the tailings dam and carry pollution into the environment through surface flow. This simplified model therefore incorporates the basic components of the risk assessment presented here.

5. Conclusion

The methodology presented here has led to the construction of a GIS model which evaluates the sensitivity of ground and surface water to pollution from mines in an area typical of the Witwatersrand Goldfields. This method is applicable not only to the pilot study area but also to many other mining regions, both in South Africa and abroad. The model can be divided into the following components:

- A tool to identify potential pollution sources.
- A tool to identify existing pollution problems.
- Tools to identify and locate potential pollution dispersal pathways into ground and surface water.
- A methodology to apply to new mining and waste disposal projects, to make these intrinsically safer.

In this model, the radioactivity of the ores and wastes is used as a diagnostic characteristic in the identification of pollution, however any such property may be used. For most cases, geochemistry, geophysics or some form of remote sensing will be used to locate pollution

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