A holistic approach towards best management practices of mine pollution impacts using a catchment area strategy, South Africa

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Abstract Historical and current gold, coal, Pt-Ni, and other mining activities severely affected the scarce water resources of South Africa. A multidisciplinary project is underway on a catchment area scale to assess mine impacts and delineate pollution hotspots. Subsequently nineteen "pollution influence areas" are delineated in the Olifants River Catchment Area. A catchment pollution atlas is then generated for ease of proper rehabilitation/remediation planning. This study proved catchment-scale multidisciplinary investigation is useful in identifying pollution sources faster and cheaper than conventional mine area approach especially for large catchments where mining are widespread, heterogeneous and of many decades of mine history.

Keywords Olifants River Catchment Area, mine pollution, pollution hotspot, pollution influence area, pollution atlas.

Introduction

In South Africa, mining pollution has historically been a major source of degradation of natural resource systems such as surface and groundwater resources and land use. Unfortunately, the current information on mining externalities is insufficient to be useful for policy setting. Extensive and systematic studies should be undertaken to fill this information gap, particularly in the development of policy instruments, which require information on social costs of mining, and partly to assist in the formulation of guidelines on damage assessment and compensation for the mining sector.

There is a need to nationally co-ordinate research, development, and application of AMD assessment and remediation techniques. In this regard, the Environmental Geosciences Unit (EGU) of the Council for Geoscience (CGS) has embarked upon a project focusing on a national holistic strategy for rehabilitation and remediation of environmental impacts and critical pollution problems from the mining industry affecting the environment and ecosystem with a particular focus on the scarce water resources.

The impact assessment component of the project began on catchment-based approach. Two major river catchment areas, the Olifants and the Komati-Crocodile, which are known to be severely affected by historical and current mining activities, have been investigated to date. The results of the investigation in the Olifants River Catchment Area (ORCA) are the subject of this paper.

The ORCA is one of the major river basins in South Africa constituting roughly 87,000 km^2 area, 85 % of which is within the South African territory and the rest in Mozambique (Ashton *et al.* 2001). It has nine secondary, 90 tertiary and 145 quaternary catchments (Fig. 1).

The Olifants River has a relatively dense network of tributary rivers and streams though most of the tributaries in the lower reaches of the catchment only have either sea-

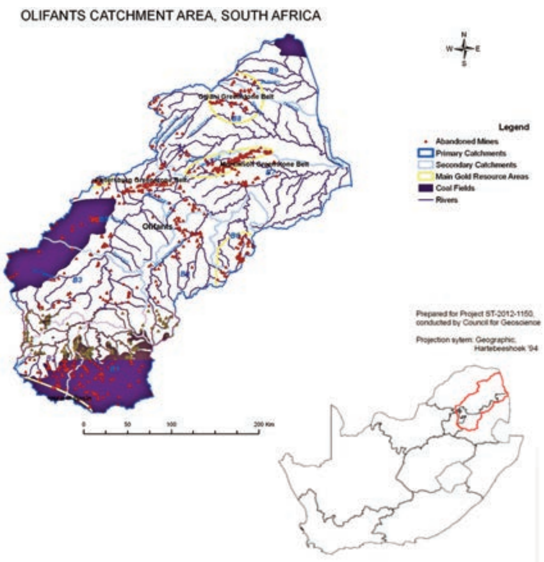

Fig. 1 *The Olifants River Catchment Area with its historical and active mines; in set -location of the catchment area within South Africa.*

sonal or episodic flows. The Olifants River flows north up to the middle portion of the catchment and makes a sharp turn towards east until it leaves the South African territory.

The geology of ORCA is part of the eastern lobe of the Kalahari Craton, which comprises predominantly crystalline granitic and gneissic rocks, intruded by various greenstone belts, dolerite dykes and sills. Silicified sedimentary formations also form part of the Archaean Craton. Karoo System rocks overlie large areas of the southwestern portion of the basin and these are associated with younger sedimentary and crystalline rocks consisting predominantly of sandstones, carbon-rich mudstone, and conglomerate and shale units. Recent sedimentary deposits line most of the river valleys and provide important farming areas (Netshitungulwana and Yibas 2012a).

The Olifants River Catchment Area hosts significant number of metallogenic (geo-environmental) provinces namely, the Archaean Greenstone Belts, the Bushveld Complex and the Witbank Coalfield, among others, which host a number of major goldfields, platinum-chromium and other PGE metal mines, coalmines, and mines of other mineral commodities such as copper and heavy minerals (Fig. 1).

Approach and Methodology

A multidisciplinary project which includes remote sensing & GIS, hydrology & water quality, hydrogeology, geochemistry, acid mine drainage assessment, ecotoxicology and geophysics, have been applied to assess the qualitative and quantitative impacts of extensive mining activities mainly on the water resources of the Olifants River Catchment Area.

A catchment scale geochemical study of stream water underlying sediments was conducted to determine their metal and anion loadings and for their current and potential AMD as well as to understand the sediment-water geochemical interaction.

Assessment of current and potential AMD from active and inactive mine infrastructures such as mine residue deposits, open pits and underground workings, have been carried out.

Hydrogeological studies including evaluation of existing data, delineation of major aquifers and qualitative characterization of surface and borehole water in and around the mine areas were undertaken based on existing information and newly acquired hydro census data. The data then was integrated and preliminary assessment of human induced flow patterns due to pumping as well as injection (if any) was done.

A catchment-scale hydrological simulation was performed to estimate runoff and infiltration.

Ground based electromagnetic and electrical geophysical methods namely frequency domain electromagnetic (FDEM) and electrode resistivity tomography (ERT), were used for mapping the depth and lateral extent of subsurface pollution plumes in areas where subsurface plumes were suspected. Geological structures were delineated using the magnetic method. In the northeastern part of the study area, geophysical surveys were carried out along the peripheral zones of mine locations.

Results and Discussions

Geochemistry

About 119 stream water and similar number of stream sediment samples were collected from systematically distributed positions in the various streams within the Olifants River Catchment Area. These samples were then analysed to assess the concentration, migration and dispersion of potentially toxic metals and anions using XRF, ICP-MS and IC methods. The sediment samples were also subjected to acid base accounting (ABA) test for current and potential AMD. Leachates have also been extracted from the sediment samples using standard water extraction technique and analysed using ICP-MS and IC methods.

On the basis of the interpretation of the geochemical data 19 pollution hotspots have been delineated throughout the ORCA in terms of metal signatures and their current and potential AMD. These hotspots drains largely on various mining areas such as the Witbank coalfield mines, the greenstone hosted gold mines such as the Sabie and Pilgrim's Rest area, the Sn and Cu mines of the Rooiberg Felsites, the copper deposit in the Phalaborwa Carbonatite Complex and small scale heavy mineral mines (Netshitungulwana and Yibas 2012a, 2012b). This study enables fingerprinting of sources of contaminants and therefore mining impact on the geochemistry of the stream water and sediment.

Acid Mine Drainage (AMD)

The main objective of the AMD assessment task is to characterize the quality and quantity of mine water drainage from operational and non-operational mine infrastructures such as surface or underground mines, mine residues deposits; and also determine the potential of the mine infrastructures to generate AMD in the future.

Fieldwork which involved site characterisation and sampling was conducted in the Olifant River Catchment Area. The fieldwork covered the mining areas of Giyani and Murchison greenstone belts, Pilgrim Rest Goldfield, eastern Limb of the Bushveld Complex, and the Witbank Coalfield (Novhe *et al.* 2013).

The gold mineralisation in Giyani Greenstone Belt is associated with quartz veins, with minor suphides, asscoaited with banded iron foramtions (BIF), and carbonate veins. Most of the gold mines are left with abandoned and unrehbilatated mine tailings deposits, open pits and shafts. Owing to the climate of the area most of the mine residue deposits are dry although the high percentage of sulphur (0.3 – 2.5 %) indicates acid generating potential of the tailings deposits. This was cofirmed during a follow up visit immediately after heavy rain, which revealed that the run-off water from one of the deposits (Osprey Gold Mine) was acidic.

The majority of antimony and gold mines of the Murchison Greenstone Belt are abandoned and only few are still operational. Large part of the inactive mine residue deposits do not show any seepage which could be attributed to the dry climate and weather of the area. However, the sulphur content ranges from 0.05 to 4 %, averaging at 0.9 % and leachates extracted from the samples yield low pH (>4) and high conductivity (> 400 mS/m). Sb, Fe, Al, Mn, Cr, As, and Co have been identified as potential pollutants.

Gold mineralisation in the Pilgrim's Rest Goldfield principally occurs within the Malmani dolomite of the Transvaal sediments. Onsite analyses of leachates from the active mine residues and return water dam showed near neutral (pH ≈ 7) which could be atributed to the buffering capacity of the carbonate host rocks. The sulphur percentage (2.6 – 18 %, averaging at 9 %) indicates, however, acid generating potential.

In the Eastern part of the Bushveld Complex, most of the mines exploit platinum and chrome from the Merensky Reef and the UG2 layer, respectively. During the the field investigation most of the mine residue deposits shows seepages of alkaline drainage with pH of 8 or higher. ABA test conducted on the collected samples indicated no potential to generate AMD. This is also evident from the very low sulphur content (0.02 – 0.04 %, averaging at 0.03 %) of the samples.

The Witbank Coalfield, situated in the southern part of the Olifant Catchment, is one of the major coal mining areas in South Africa. Coal is extracted by means of both open cast and underground mining method from depths of a few meters to about 300 metres. Both abandoned and operational mines dischrage acid mine drainage (AMD) in various forms. In some cases AMD discharges directly into the streams. Generally, the AMD in the Witbank Coalfield is characterised by low pH (<3) and high concentration of metals (Fe, Al, Mn) and sulphate and TDS. The sulphur content ranges from 0.4 to 7 %, averaging at 2.7 %, pyrite as the major sulphide mineral. Acid base accounting (ABA) tests indicate high acid generating potential (AP) and low neutralization potential (NP). Leachates extracted from the samples indicate Fe, Al, Mn, Cr, and As as potential pollutants (Novhe *et al.* 2013).

The AMD assessment summarised above is used to delineate AMD hotspots in the Olifants River catchment area. The AMD hotspots identified tied well with and corroborated the pollution hotspots identified from surface water and stream sediment geochemistry.

Hydrogeology

Preliminary hydrogeological assessment was conducted in the Murchison, Giyani and Pilgrim's Rest greenstone gold mines, in the Burgersport platinum (and chromium) mines in the eastern part of the Bushveld Complex, and in the Phalaborwa Carbonatite copper and phosphate mine area.

Groundwater samples collected from mines monitoring boreholes and from farm boreholes as well as surface water samples from within and around the mining areas, showed elevated cocentrations of certain species such as NO_3, As, Fe, Al, Mn, and rarely Cu, SO_4, Cl, F, albeit variably, in the different mines of the catchment. Aresenic (As) is the most common contaminant cation exceeding both drinking water as well as SANS (South African National Standard) limits in the five out of the six mine areas investigated. Al, Fe and Mn each showed elevated concentrations in three out of the six mine areas. The most common anion contaminants are NO_3 and Cl, each of which show elevated concentration in three out of the six mine areas. SO_4, F and Cl show elevated concentrations in the three separate mine areas co-elevated only in one.

The pollution hotspots identified using the hydrogeological investigation in the six mining areas in the Olifants River Catchment Area are well in agreement with the pollution hotspots delineated using the stream water and sediment geochemistry as well as from AMD potential assessment studies.

Ground Geophysical Survey

The depth and lateral extents of contaminant plumes were mapped in the southern and northern parts of the catchment using geophysical techniques that comprised Frequency Domain Electromagnetic (FDEM) and electrical resistivity tomography (ERT). Contaminant pathways associated with high electrical conductivity values were delineated at some mining locations in the northeastern part of the study area (Nyabeze *et al.* 2012). The results confirmed the existence of near surface high electrical conductivity zones that were interpreted as shallow AMD plumes. Dykes, faults and geological contacts were delineated from magnetic profile data. The use of geophysical techniques proved to be an effective tool for mapping out contaminant plumes specifically in the Barberton, Giyani and Witbank areas.

Hydrology

Catchment-scale annual and single event runoff depth and infiltration distribution were simulated for the Olifants River Catchment Area using the GIS based RINSPE (Runoff, Infiltration and Non-point Source Pollution Estimation) model (Thomas *et al.* 2010). The total annual rainfall volume received in the catch-

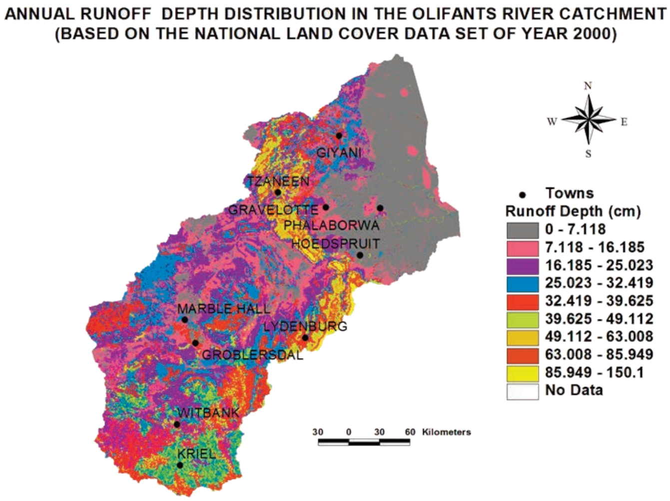

***Fig. 2** Annual runoff simulation results for the Olifants Catchment.*

ment is 44.6 Gm³. The total volume of cumulative infiltration in a year is 6.4 Gm³ (14.46 % of the rainfall volume whereas the total annual volume of surface runoff (direct runoff) is 16.6 Gm³ (37.2 % of the rainfall volume). The runoff modeling result (Fig. 2) showed that high annual runoff depths characterize the Greenstone Goldfield mine areas in the central part of the catchment (near Tzaneen) and the Witbank Coalfield area in the south. This indicates the contribution of polluted runoff from these areas of intense past and current mining activities towards downstream of the catchment is high (Fig. 2). The Kruger National Park area has the lowest runoff (0 – 7.118 cm) whereas the area around Tzaneen has maximum runoff (85.949 – 150.1 cm).

Summary and Conclusions

Catchment Pollution Atlas

Mine pollution atlas map has been prepared for the Olifants River Catchment Area after integrating the findings of: a) catchment-scale stream water and sediment geochemistry, b) catchment-scale hydrological study for runoff and infiltration estimation; c) mine area-scale investigations of hydrogeology, current and potential AMD assessment, and ground geophysical surveys for shallow subsurface plumes. The atlas (Fig. 3) shows in addition to the polluted areas, pollution sources and the pollution pathways, together forming what is herein termed as "mine pollution influence areas". Nineteen such pollution influence areas are delineated. Eight of the 19 pollution influence areas are within the Witbank Coalfield

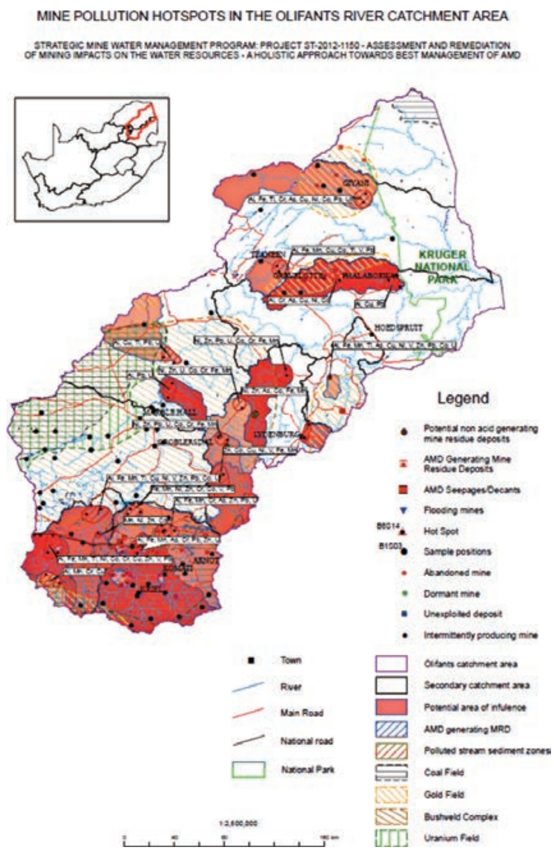

***Fig. 3** Pollution atlas of the Olifants Catchment area generated based on multidisciplinary pollution characterization.*

confirming the severity of mining pollution in the coalfield. The eight pollution influence areas could be integrated into two major pollution areas.

Conclusion

This study shows that catchment-scale mine pollution study using a multi-disciplinary approach with the understanding of geo-environmental provinces proved powerful and meaningful than focusing on a number of separate localized mine-scale studies.

Such catchment-scale investigation provides a holistic understanding of mine pollution from pollution source to pathways to receiving environment (source-pathways-recipient dynamics) – herein termed as "mine pollution influence areas". Nineteen such pollution influence areas have been delineated. Eight of the 19 pollution influence areas are within the Witbank coalfield confirming the severity of mining pollution in the coalfield.

The multi-disciplinary approach also proved effective in providing multiple source of scientific information and integrating such multi-disciplinary scientific data improves the reliability and accuracy of the findings. The study provides a powerful management tool for the remediation and rehabilitation of pollution influence areas, which encompasses the source, the pathways and the receiving areas of pollution. This is particularly relevant in mining countries such as South Africa where the legacies of over a century of mining activities affected not only mining areas but also areas of tens of square kilometers which crosses catchment boundaries.

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References

Ashton P, Love D, Mahachi H, Dirks P (2001) An overview of the impact of mining and mineral processing operations on water resources and water quality in the Zambezi, Limpopo and Olifants catchments in southern Africa, Contract Report to the Mining, Minerals and Sustainable Development (SOUTHERN AFRICA) Project, by CSIREnvironmentek, Pretoria, South Africa and Geology Department, University of Zimbabwe, Harare, Zimbabwe. Report No. ENV-P-C 2001–042. xvi + 336 pp

Netshitungulwana R and Yibas B (2012a) Investigations of the stream sediments geochemistry for the metal pollution sources of the Olifants River Catchment, Technical Report, Council for Geoscience, unpublished report, pp87.

Netshitungulwana R and Yibas B (2012b) Stream sediment geochemistry of the Olifants catchment, South Africa: Implication for acid mine drainage. In: McCullough CD, Lund MA, Wyse L, 2012 International Mine Water Association Symposium, Bunbury, Western Australia, 257–264

Novhe NO, Netshitungulwana R, Yibas B, Motlakeng, T, Sakala E (2013), Metal pollution sources and transport in mined watershed: an insight from Ermelo Coalfield, South Africa (IMWA 2013, this volume).

Nyabeze P. K., Yibas B. and Sakala E. (2012). Conference Paper: Investigation of contaminant plumes emanating from residual mine deposits in the Limpopo Province of South Africa, results from geophysical surveys. GeoManitoba 2012 Conference, Manitoba, Canada.

Thomas, A., Chingombe, W., Ayuk, J. and Scheepers, T. 2010. 'A Comprehensive Investigation of the Kuils-Eerste River Catchments Water Pollution and Development of a Catchment Sustainability Plan'. Water Research Commission (WRC) Report No. 1692/1/10. ISBN 978-1-4312-0016-0. September 2010.