

TABLE OF CONTENTS

EXECUTIVE SUMMARY	viii
1. INTRODUCTION.....	ix
2. OBJECTIVES OF THE STUDY	ix
3. METHODOLOGY	ix
4. GOLD MINE TAILINGS AS A POTENTIAL POLLUTION SOURCE FOR THE SUBSURFACE	x
4.1 Impact on the unsaturated zone.....	x
4.2 Impact on the saturated zone.....	xii
5. DISCUSSION AND CONCLUSIONS.....	xiii
6. RECOMMENDATIONS	xvi
 CHAPTER 1 – INTRODUCTION.....	 1
1.1 MOTIVATION	1
1.2 OBJECTIVES OF THE STUDY	3
1.3 SCOPE OF INVESTIGATIONS	4
1.4 PREVIOUS WORK AND RELATED STUDIES.....	5
1.5 REPORT STRUCTURE	9
1.6 REPORT RESPONSIBILITIES.....	10
1.7 CONFIDENTIALITY OF SITE DATA	10
 CHAPTER 2 – GOLD-MINE RESIDUE DEPOSITS IN SOUTH AFRICA	 11
2.1 INTRODUCTION.....	11
2.2 LEGISLATION.....	12
2.3 CLASSIFICATION OF MINE RESIDUE DEPOSITS.....	13
2.3 DEPOSITION APPROACHES IN THE ESTABLISHMENT OF TAILINGS IMPOUNDMENTS	15
2.4 GEOHYDROLOGICAL CONDITIONS OF TAILINGS DAMS	17
2.4.1 Seepage losses from tailings dams.....	18
2.4.2 Seepage control approaches	19
2.5 RECLAMATION OF MINE RESIDUE DEPOSITS	19
2.6 LAND USE AFTER RECLAMATION.....	20
2.7 REGISTER FOR GOLD MINE RESIDUE DEPOSITS	21
2.7.1 The use of GIS as a supporting tool for the establishment of a register.....	21
2.7.2 GIS-based register for gold-mine residue deposits	21
2.7.3 Statistical evaluation of the register	22
2.7.3.1 Classification of gold-mine residue deposits	23
2.7.3.2 Spatial distribution of gold-mine residue deposits	25
2.7.3.3 Geological conditions beneath gold-mine residue deposits	26
2.7.3.4 Land use in close proximity to gold-mine residue deposits	27

CHAPTER 3 – GEOHYDROLOGY OF THE UNSATURATED AND SATURATED ZONES		30
3.1	INTRODUCTION	30
3.2	UNSATURATED ZONE 30	
3.2.1	Basic concepts for the unsaturated zone	30
3.2.2	Behaviour of a fluid in an unsaturated porous medium	31
	3.2.2.1 <i>Capillary forces</i>	32
	3.2.2.2 <i>Adsorption forces</i>	33
3.2.3	Specific retention and storage capacity.....	34
3.2.4	Preferential flow-paths in the unsaturated zone	35
3.2.5	Mass transport in the unsaturated zone	36
3.3	SATURATED ZONE	37
3.3.1	Basic concepts of the saturated zone.....	37
3.3.2	Hydrologic characterisation of the saturated zone	37
3.3.3	Mass transport in the saturated zone	38
	3.3.3.1 <i>Diffusion</i>	38
	3.3.3.2 <i>Advection</i>	39
	3.3.3.3 <i>Dispersion</i>	40
CHAPTER 4 – ENVIRONMENTAL HYDROGEOCHEMISTRY		42
4.1	INTRODUCTION	42
4.2	BASIC HYDROGEOCHEMICAL PROCESSES IN THE SUBSURFACE	44
4.2.1	The equilibrium concept and deviation from equilibrium	45
4.2.2	Kinetic approach	47
4.2.3	Precipitation and dissolution reactions.....	49
4.2.4	Ion exchange and sorption processes	51
4.2.5	Reduction and oxidation processes	54
4.3	THE CONCEPT OF BACKGROUND VALUES	58
4.4	HYDROGEOCHEMICAL PROCESSES WITHIN MINE TAILINGS	59
4.4.1	Introduction	59
4.4.2	Sulphide oxidation and acid generation processes (AMD).....	60
	4.4.2.1 <i>Primary factors</i>	61
	4.4.2.2 <i>Secondary factors</i>	64
	4.4.2.3 <i>Tertiary factors</i>	65
	4.4.2.4 <i>Downstream factors</i>	66
4.4.3	CHEMISTRY AND MINERALOGY OF GOLD-MINE TAILINGS	67
	4.4.3.1 <i>Background – Chemistry and mineralogy of the Witwatersrand reefs</i>	67
	4.4.3.2 <i>Mineralogical composition of gold-mine tailings</i>	69
	4.4.3.3 <i>Chemical composition of gold-mine tailings</i>	70
4.5	GEOCHEMICAL STABILITY OF CONTAMINANTS	72
4.5.1	Introduction	72
4.5.2	Geochemical stability.....	73
4.5.3	Remobilisation of trace elements from gold-mine tailings	75
4.6	TOXICITY	77
4.6.1	Introduction	77
4.6.2	Toxicity of selected contaminants.....	78
	4.6.2.1 <i>Sulphate</i>	78
	4.6.2.2 <i>Arsenic</i>	78
	4.6.2.3 <i>Cobalt</i>	79

	4.6.2.4 Chromium.....	79
	4.6.2.5 Copper	80
	4.6.2.6 Iron	80
	4.6.2.7 Nickel	80
	4.6.2.8 Manganese.....	81
	4.6.2.9 Lead	81
	4.6.2.10 Zinc	81
	4.6.2.11 Cyanide	82
	4.6.2.12 Radioactive elements.....	82
4.7	ENVIRONMENTAL HAZARDS FOR THE AQUATIC PATHWAY CAUSED BY AMD AND ASSOCIATED CONTAMINANTS.....	84
	4.7.1 Introduction	84
	4.7.2 Impact of AMD and trace elements on the unsaturated and saturated zones	84
CHAPTER 5 – METHODOLOGY		86
5.1	DATA COLLECTION	86
	5.1.1 Development of a GIS-linked database for gold-mine tailings dams	87
	5.1.2 Field survey	88
5.2	LABORATORY TESTING	88
	5.2.1 Extraction tests	89
5.3	DATA EVALUATION	91
	5.3.1 Background concentrations.....	91
	5.3.2 Environmental evaluation and classification of case study sites.....	91
	5.3.3 Assessment of the current pollution impact.....	92
	5.3.4 Assessment of the potential future pollution impact.....	93
	5.3.5 Estimation of hydraulic conductivities.....	95
	5.3.6 Description of soil types occurring in the study area	96
CHAPTER 6 – CASE STUDIES		97
6.1	INTRODUCTION	97
6.2	AVAILABLE INFORMATION	98
6.3	REGIONAL SETTING	99
	6.3.1 Regional Climate	100
6.4	CASE STUDIES	102
	6.4.1 Case study site A	103
	6.4.2 Case study site B	107
	6.4.3 Case study site C	111
	6.4.4 Case study site D	114
	6.4.5 Case study site E	119
	6.4.6 Case study site F	123
	6.4.7 Case study site G	127
	6.4.8 Case study site H	131
	6.4.9 Case study site I	133
	6.4.10 Case study site J	138
	6.4.11 Case study site K	142

6.5	SUMMARY OF CONTAMINANT ASSESSMENTS.....	145
6.5.1	Case study A	145
6.5.2	Case study B	145
6.5.3	Case study C	146
6.5.4	Case study D	146
6.5.5	Case study E	147
6.5.6	Case study F	148
6.5.7	Case study G	149
	OTHER SITES	150
6.5.8	Case study H	150
6.5.9	Case study I	150
6.5.10	Case study J	151
6.5.11	Case study K	152
	CHAPTER 7 – IMPACT ASSESSMENT	153
7.1	INTRODUCTION	153
7.2	CHARACTERISATION OF THE PRIMARY POLLUTION SOURCE	154
7.3	CURRENT POLLUTION IMPACT ON THE SUBSURFACE	155
7.3.1	Unsaturated zone (vadose zone).....	155
7.3.2	Saturated zone (groundwater system)	163
	7.3.2.1 <i>Regional groundwater quality</i>	163
	7.3.2.2 <i>Groundwater quality in the study area</i>	164
7.4	FUTURE POLLUTION IMPACT POTENTIAL ON THE SUBSURFACE.....	165
7.4.1	Impact on the unsaturated zone.....	165
7.4.2	Impact on the saturated zone.....	167
	CHAPTER 8 – PRELIMINARY REHABILITATION MANAGEMENT	169
8.1	INTRODUCTION	169
8.2	REHABILITATION OPTIONS FOR CONTAMINATED SOILS	171
8.2.1	Treatment technologies	172
8.2.2	On-site management.....	174
	8.2.2.1 <i>Vegetation cover for reclaimed sites</i>	176
8.3	REMEDICATION OF GROUNDWATER CONTAMINATED BY AMD AND ASSOCIATED CONTAMINANTS	177
8.4	LONG-TERM ENVIRONMENTAL MANAGEMENT FOR LARGE-SCALE CONTAMINATED SITES	178
8.5	MONITORING AS INTEGRAL PART OF REHABILITATION MANAGEMENT	180
8.6	RISK ASSESSMENT	180
	CHAPTER 9 – DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS	183
9.1	DISCUSSION	183
9.2	CONCLUSIONS	184
9.3	RECOMMENDATIONS	188
	CHAPTER 10 – LIST OF REFERENCES	190

LIST OF TABLES

Table 2.1 :	Parameters and Source Information Captured in the GIS-linked database	22
Table 2.2 :	Statistical Parameters of Gold Mine Residue Deposits and Reclaimed sites	22
Table 2.3 :	Classification of Gold Mine Residue Deposits with regard to the covered area size	23
Table 2.4 :	Summary of the Frequency of Gold Mine Deposits	24
Table 2.5 :	Geological conditions under gold mine residue deposits	25
Table 3.1 :	Typical values of some properties of common clay minerals.....	33
Table 4.1 :	Important processes as sources of different ions and processes that may limit the concentration of ions in fresh water	42
Table 4.2 :	Solubility products of common minerals in the aqueous phase.....	49
Table 4.3 :	Selected elements that can occur in more than one oxidation state in groundwater systems.....	52
Table 4.4 :	Redox classification for different chemical environments	53
Table 4.5 :	Mean analytical values for significant minerals and uranium present in Vaal Reef and VCR samples	66
Table 4.6 :	Trace element contents of pyrites of the Black Reef formation	67
Table 4.7 :	Summary of statistics for major element concentrations contained in tailings samples	68
Table 4.8 :	Summary of statistics for trace elements concentrations contained in tailings samples	70
Table 4.9 :	Relative mobilities of elements in sediments and soils as a function of Eh and pH	75
Table 5.1 :	Summary of laboratory tests, the number of samples and the method applied	86
Table 5.2 :	Extractable NH_4NO_3 threshold values for soils	88
Table 5.3 :	Average background values in top soils obtained from the Vryheid Formation and Malmani Subgroup.....	89
Table 5.4 :	Recommended maximum NH_4NO_3 extractable threshold concentrations that should not be exceeded in the soil.....	90
Table 5.5 :	Pollutant enrichment classes by using the geochemical load index	92
Table 5.6 :	Average range for the abundance of selected trace elements in soils.....	92
Table 5.7 :	Comparison of tables of the Unified Soil Classification Classes and related Hydraulic Conductivity	93
Table 6.1 :	Important features of the selected case study sites	98
Table 6.2 :	The average monthly rainfall and maximum 24-hour rainfall and evaporation for the Johannesburg Area	100
Table 6.3 :	Average monthly maximum and minimum temperatures for the Johannesburg Area	101
Table 6.4 :	Seepage analysis showing the macro-chemistry at Site D.....	118
Table 6.5 :	Seepage analysis showing the micro-chemistry at Site D	119
Table 6.6 :	Groundwater quality at Site F	127
Table 6.7 :	Seepage analysis showing the macro-chemistry at Site G.....	130
Table 6.8 :	Seepage analysis showing the micro-chemistry at Site G	130
Table 6.9 :	Macro-chemistry of a groundwater sample obtained at Site H.....	133
Table 6.10:	Heavy metal concentration ranges in pH values at Site I	137
Table 6.11:	Average values for selected water quality parameter at Site J.....	139

Table 6.12:	Average trace element concentrations at Site J.....	140
Table 6.13:	Surface water quality with increasing distances downstream of Site J	140
Table 6.14:	Summary of statistics for trace element concentrations contained in soil and sediment samples in close proximity to Site J.....	141
Table 7.1 :	Statistical parameters of the bio-availability of trace elements	154
Table 7.2 :	Threshold exceedance ratios of soil samples obtained from Site F	155
Table 7.3 :	Trace element mobility and main statistical parameters in soil samples obtained from Site F.....	156
Table 7.4 :	Calculated geochemical load indexes for various trace elements.....	166

LIST OF FIGURES

Figure 2.1 :	Photograph of a partly reclaimed tailings dam in the East Rand area	15
Figure 2.2 :	Typical layout of a tailings dam.....	16
Figure 2.3 :	Position of the phreatic surface in a tailings dam during operation and after decommission	17
Figure 2.4 :	Distribution of frequencies with regard to <i>Class A</i> gold mines tailings dam.....	23
Figure 2.5 :	Spatial distribution of gold mine residue deposits related to provinces and covered land size	25
Figure 2.6 :	Mine residue deposit distribution according to geological strata classification	27
Figure 2.7 :	Land use in close proximity to gold mine residue deposits	28
Figure 2.8 :	Satellite image of the Johannesburg area.....	29
Figure 4.1 :	Schematic overview of processes affecting water quality in the hydrological cycle	42
Figure 4.2 :	The concept of equilibrium and kinetics.....	47
Figure 4.3 :	Schematic description of various sorption processes.....	50
Figure 4.4 :	Distribution of heavy metals over various sorption phases in the soil	51
Figure 4.5 :	Sequence of reduction processes with increasing depth in the unsaturated and saturated zones.....	54
Figure 4.6 :	Mineral distribution in gold mine tailings	68
Figure 4.7 :	Eh – pH fields for some common aquatic environments.....	73
Figure 4.8 :	Eh – pH stability relationships between ion oxides, sulphates and carbonates in the aqueous phase	73
Figure 5.1 :	Estimation of saturated hydraulic conductivity in a fine-grained soil	93
Figure 6.1 :	Map of South Africa indicating the study area	99
Figure 6.2 :	Locality map of the case study sites south of Johannesburg	102
Figure 7.1 :	Conceptual model of the pollution source and the affected subsurface	153
Figure 7.2 :	Relation between soil depth and soil pH in the study area	157
Figure 7.3 :	Ni mobility as a function of pH	158
Figure 7.4 :	Cr mobility as a function of pH	158
Figure 7.5 :	Cu mobility as a function of pH.....	159
Figure 7.6 :	Fe mobility as a function of pH	159
Figure 7.7 :	Co mobility as a function of pH.....	160
Figure 7.8 :	Pb mobility as a function of pH.....	160

Figure 7.9 :	U mobility as a function of pH	160
Figure 7.10:	Zn mobility as a function of pH.....	160
Figure 7.11:	As concentration in soils as a function of depth	162
Figure 7.12:	Zn concentration in soils as a function of depth	162
Figure 8.1 :	Association between the master variables, the major element cycles and contaminants	179
Figure 8.2 :	Stages in a risk assessment procedure	181

LIST OF APPENDICES

Appendix A:	Geotechnical profiles, geotechnical and geochemical descriptions	
Appendix B:	Summary of geochemical analyses, background values for Vryheid Formation, correlation matrices for the tailings and soil analyses	
Appendix C:	Mineralogical analyses of mine residue samples	
Appendix D:	Register for mine residue deposits in South Africa	
Appendix E:	Maps with all mine residue deposits of the register	
Appendix F:	Site photographs 1-12	

ABBREVIATIONS AND ACRONYMS

ABV	Average background value
AEC	Anion Exchange Capacity
Alk	Alkalinity
AMD	Acid mine drainage
AVG	Average (mean value)
CEC	Cation exchange capacity
CL	Crisis limit
EC	Electrical conductivity
EMP	Environmental management plan
EMPR	Environmental management plan report
ICP-MS	Induced coupled plasma mass spectrometer
K	Hydraulic conductivity (m/s)
LOI	Loss on ignition
MAX	Maximum value
mg/l / mg/kg	1 mg/kg = 1/1000 g/kg (10 ⁻⁶ g/l)
MIN	Minimum value
MOB	Mobility in % (bio-availability)
n	Population of samples
n. a.	Information not available
n/d	Not detectable
NAPL	Non aqueous phase liquids
NGDB	National Groundwater Database, RSA
nm	Nano metre (10 ⁻⁹ m)
NTP	Normal temperature and pressure
P&T	Pump-and-treat approach
PI	Plasticity index
QA/QC	Quality control/quality assessment
RDP	Reconstruction and development program
RML	Recommended maximum limit
RSA	Republic of South Africa
SAR	Sodium adsorption ratio
STDEV	Standard deviation
TC	Threshold concentration
TCLP	Toxic characteristic leaching procedure
TDS	Total dissolved solids
TER	Threshold exceedance ration
µg/l	1 µg/l = 1/1000 mg/l (10 ⁻⁹ g/l)
XRD	X-ray diffraction analysis
XRF	X-ray fluorescence analyses

Government Departments, institutions and consulting firms

ASTM	American Society for Testing and Materials
DME	Department of Minerals and Energy, RSA
DWAF	Department of Water Affairs and Forestry, RSA
NRC	National Research Council, USA