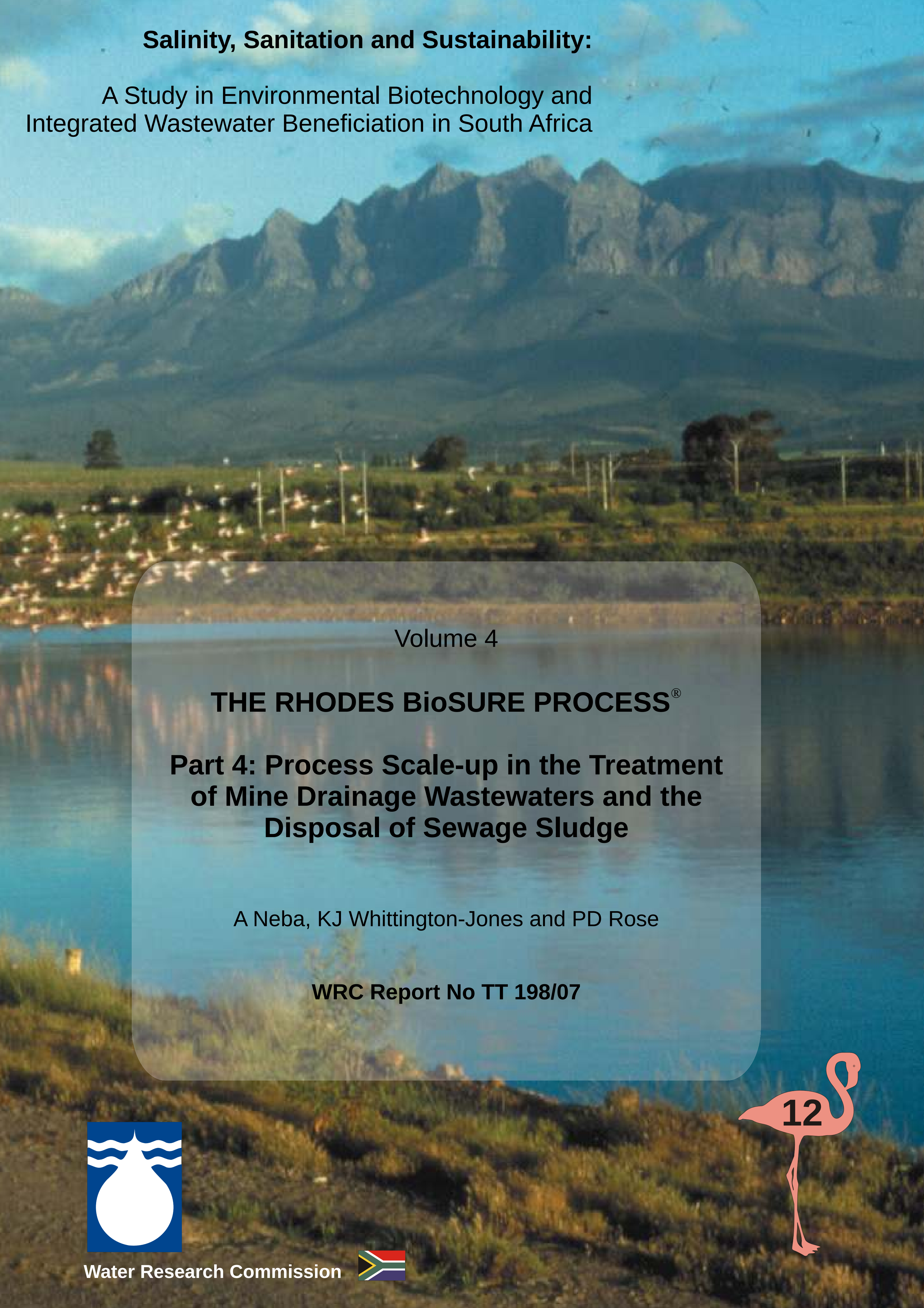

Salinity, Sanitation and Sustainability:

A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa

Volume 4

THE RHODES BioSURE PROCESS®

Part 4: Process Scale-up in the Treatment of Mine Drainage Wastewaters and the Disposal of Sewage Sludge

A Neba, KJ Whittington-Jones and PD Rose

WRC Report No TT 198/07

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Water Research Commission

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Part 4: Process Scale-up in the Treatment of Mine Drainage Wastewaters and the Disposal of Sewage Sludge

Report to the Water Research Commission

by

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WRC Report No: TT 198/07
September 2007

Obtainable from:

Water Research Commission
Private Bag X03
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0031

The publication of this report emanates from Water Research Commission Projects K5/1169 'Intermediate scale-up evaluation of the Rhodes Process for hydrolysis and solubilisation of sewage sludges in a sulphate reducing bacterial system'; K5/1291 'Managerial inputs into operationalisation of the Rhodes BioSURE Process at ERWAT', and Part 2 of K5/1456 'Biotechnological co-treatment of saline and sewage wastewaters with integrated recovery and reuse of water and organic and inorganic components for sustainable development. Part 2: Bio-sulphidogenic Sewage Treatment'.

Project Leader: Prof P.D. Rose

ISBN: 978-1-86845-895-0
Set No: 1-86845-853-9

Printed in the Republic of South Africa

FOREWORD

The work presented in this series covers a decade of concerted research into critical sustainability issues in the water-scarce Southern African situation. The provision of safe and adequate drinking water and sanitation services to all our people remains a challenge. Pervasive salination from a range of mining, industrial and agricultural activities threatens the quality of our water resources. Simultaneously, the complex ecological needs of the aquatic environment are being understood with ever-increasing clarity.

Significant progress has been made in meeting some of these challenges. In the years since the democratic elections of 1994, millions of previously unserviced South Africans have been supplied with safe drinking water and sanitation services. The problem of increasing salinity of our water resources, with its direct economic impacts and future threat to sustainability, is being addressed at policy and implementation levels, for example by reduction-at-source measures. The ecological needs of the aquatic environment have been recognised by the provision in our water law of a prioritised ecological reserve, to be managed by the catchment management agencies being formed.

Such promising developments notwithstanding, ultimately sustainable resolution of these issues depends crucially also on acquiring appropriate and affordable technologies that provide physical solutions to our water-related challenges. It is in this context that the research described in this series deserves special commendation for the highly innovative biotechnological linkage developed between the treatment of saline wastewaters on one hand and domestic sewage and sludges on the other.

In the novel approach followed, salinity and sanitation issues are each viewed essentially as a resource base (rather than simply as “waste problems”) in a suite of integrated process schemes which can be variously manipulated to deliver products of treated water, recovered nutrients and metals, and algal biomass. The paradigm is consequently changed from one of “managing problems” to one of “engineering opportunities”, with the potential of offering a major contribution towards the management of water and sanitation in the RSA - some applications have already been taken to full scale implementation, for example in the accelerated digestion of sewage sludge. Significantly, the achievements of this research add weight to biotechnology as “the” technology of the 21st century.

So, as we approach the World Summit on Sustainable Development, we can reflect on the provisions of Agenda 21 adopted after the Earth Summit some 10 years ago, and note that in this time we have ourselves in various ways “done something” about our own situation. And we can therefore point with a justifiable sense of pride and achievement to the body of work presented here as being “Made in South Africa”, at a time when social, environmental, political and economic calls are being made to all of Africa to stand up in the continental and global communities of nations.

My deep thanks and appreciation go to the Water Research Commission for the foresight in funding this work, and, in particular, to Prof Peter Rose and his research team at Rhodes University, for the vision, purposefulness, innovation and application with which this work has been conceived and executed.

Minister of Water Affairs and Forestry
Pretoria
31 July 2002

EDITOR'S NOTE

In 1990 the Water Research Commission, under the (then) Executive Director Dr Piet Odendaal, appointed the Environmental Biotechnology Group at Rhodes University, led by Prof Peter Rose, to carry out a one-year feasibility study to evaluate the potential of a biotechnological approach to the linked treatment and management of saline and sanitation wastewaters with recovery of useful components such as nutrient bio-products.

In the intervening years, this seminal project has resulted in a rich research programme, managed initially by Dr Oliver Hart, subsequently by Zola Ngcakani, and latterly (since 1997) by myself. The progression of the research programme is reflected in this series of reports. Report 1 critically reviews the main arguments considered in the sustainability discourse and their relation to salinity and sanitation, and presents an overview of the work covered in the individual Reports 2 – 12, each of which deals with specific aspects of the research programme. The reports are also to be issued on CD.

The research period concerned spans approximately the decade between the Rio Earth Summit in 1992 and the imminent World Summit for Sustainable Development in Johannesburg. During this time, international concern has been expressed about the limited extent to which the sustainability objectives formulated at Rio, as captured for example in Agenda 21, have been followed through to implementation.

By contrast, it is a noteworthy achievement of this research programme that the "sustainable biotechnology" originally conceptualised by the researchers has in fact, by dint of rigorous research development, experimentation and testing, been translated into a suite of practicable processes for delivering treated water as well as value-adding organic and inorganic co-products. In some applications, full-scale plants are already being installed, fulfilling the cycle of research → development → implementation.

It is probably fair to say that the full potential of the original work initiated twelve years ago, with its various applications as they have been developed since then, could at inception only have been dimly foreseen – which, with hindsight, underscores the clarity, breadth and depth of the originators' vision.

It has been a pleasure and a privilege to be involved with this work, as Research Manager and now as Editor of this series. I am confident that you, the reader, will find the contents both informative and as stimulating as I have.

Greg Steenveld
Water Research Commission
Pretoria
31 July 2002

PREFACE

This report is one of a series of twelve Water Research Commission studies undertaken by the Environmental Biotechnology Group at Rhodes University on biotechnology and integration in the management of saline and sanitation wastewater systems. Environmental problems in these areas are reckoned to be responsible for six of the seven priority pollution issues undermining the sustainable development project in Southern Africa. While both salinity and sanitation has separately been the subject of quite extensive investigation, relatively little has been reported on the potential linkage of these systems in meeting sustainable development objectives.

At the time these studies commenced in 1990, focus on the operationalisation of the sustainability idea had identified 'integrated waste resource management' as a key requirement for progress towards 'closed systems' production. Here human activities, and the associated technological environment, would be detached as far as possible from the bio-physical environment related to natural systems. Waste recovery, recycle and reuse had emerged as major strategies for achieving the radical shift to new technologies which would enable societies to live off nature's income, rather than consuming its capital. Waste beneficiation (a term still more common in the traditional resources sector, and referring to operations that add value by transforming raw material into finished products), was seen as a means of placing treatment operations on an economic footing, with value added in the form of products and services accrued in the waste management operation.

To meet the time-scale of the sustainability agenda, the breakthroughs in technology required would have to be initiated now to guarantee their availability in the next 2 to 4 decades. This led to widespread use of technology-push approaches in sustainable technologies research.

The principal aim of this programme was thus to investigate potential in environmental biotechnology for the development of technological enablement in the linkage of saline and sanitation wastewater management. This involved initial studies in the biology of organic saline wastewater impoundments and an evaluation of the recovery of nutrient values in these wastes in the form of high-value bio-products produced by halophilic micro-organisms. Integrated Algal Ponding Systems were investigated as a 'core technology' in delivering these objectives.

A critical path research methodology was used to identify technological constraints in the organic saline wastewater treatment operation and served to prioritise the research inputs required to underpin bioprocess development. Studies in the microbial ecology and environmental biotechnology of these systems provided the basis for bio-process innovation, and the subsequent development of treatment processes to full-scale engineered applications.

This series includes an introductory volume which provides an overview of the twelve-year programme to date. The reports are listed inside the front cover, and each study in the series is identified by a 'racing flamingo' number, which also appears on the outside cover. This relates to the appearance of a large flock of flamingos, which took up residence on tannery wastewater ponds following the installation of the *Spirulina*-based Integrated Algal Ponding System developed in the initial studies in this series. The development of the 'Salinity, Sanitation and Sustainability' programme is outlined below in Figure P1, and shows studies in the integrated algal ponding of saline, and domestic and industrial wastewaters, leading to the Rhodes BioSURE Process®, which provides linkage in the treatment of sulphate saline wastewaters and sewage sludge disposal.

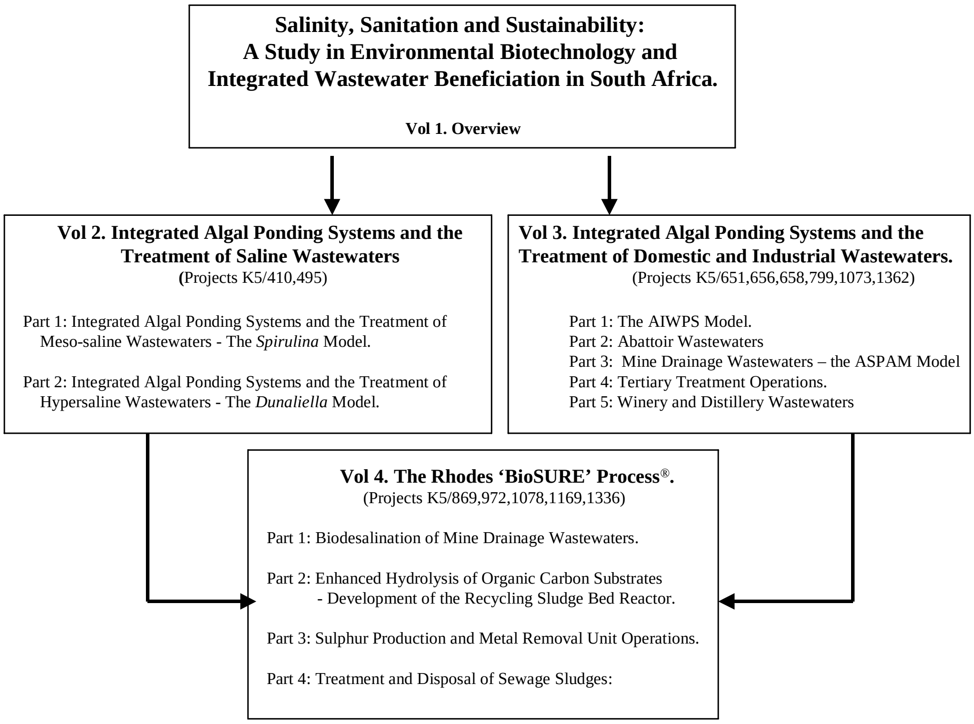

Figure P1. Research projects undertaken as components of the Water Research Commission study 'Salinity, Sanitation and Sustainability'.

A large number of people have assisted generously in many ways in the development of these studies, and are thanked under Acknowledgments. The support of former Water Research Commission Executive Director, Dr Piet Odendaal, is noted in particular. His vision of research needs in water resource sustainability in the period leading to the Rio Earth Summit in 1992 not only contributed to this study but also initiated early contributions to sustainable development research in water and sanitation service provision to developing communities. His inputs, together with Research Managers Dr Oliver Hart, Mr Zola Ngcakani, and Mr Greg Steenveld, have made substantial contributions to the development of the ideas investigated in these studies. The contribution and enthusiasm of my post-graduate research students is beyond measure.

Peter Rose
Environmental Biotechnology Research Unit
Rhodes University
Grahamstown

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EXECUTIVE SUMMARY

1 BACKGROUND

The generation of mine water pollution, both during and after mining operations, has characterised the industry worldwide since ancient times (Banks *et al.*, 1997; Brown *et al.*, 2002; Younger *et al.*, 2002; Luptakova and Kusnierova, 2005; Akcil and Koldas, 2006). In the case of acid mine drainage (AMD) waste waters, the problem may persist for many decades to thousands of years (Nordström and Alpers, 1999; Kalin, 2001). These waters are generally characterised by reduced pH, elevated levels of a range of heavy metal contaminants, most notably iron, and salts such as sulphates and chlorides (Johnson, 1995; Brown *et al.*, 2002; Cocos *et al.*, 2002; Johnson *et al.*, 2002; Costello, 2003; Akcil and Koldas, 2006). The environmental consequences of mine water pollution have been comprehensively reviewed by Lyew and Sheppard, 2001; Brown *et al.*, 2002; Younger *et al.*, 2002; Rose, 2002 and Younger, 2004.

The mine water drainage problem is of particular concern in South Africa where the threat to the limited fresh water resource is compounded by the long time periods, decades to centuries, over which decanting mine waters may be expected to flow (Funke *et al.*, 1991, Younger, 1994, Scott, 1995). Incorporation of principles of sustainability in the response to the problem has been outlined in a comprehensive programme of environmental legislation (Bosman and Kotzé, 2005). The corporate response to sustainability in mining and minerals industry operations has been extensive and includes the Berlin Guidelines (Hinde, 2000; United Nations, 2002a), and, in South Africa, the King II Report on Corporate Governance (Institute of Directors in Southern Africa, 2002) and the Johannesburg Stock Exchange Socially Responsible Investment Index (Johannesburg Stock Exchange, 2005). The triple bottom line (TBL) basis of sustainability accounting, which incorporates environmental, social and economic components of sustainability, has generally been adopted by the mining industry in South Africa (Elkington, 1988; McNeill, 2000; Gibson, 2001).

As a result, considerable attention has thus been directed at the investigation and development of cost-effective and sustainable remediation solutions for the mine water problem and the field has been the subject of extensive review (Brown *et al.*, 2002; Diels *et al.*, 2002; Gibert *et al.*, 2002; Rose, 2002; Younger *et al.*, 2002; Bowell, 2004; Johnson and Hallberg, 2005; Kalin *et al.*, 2006; Zagury *et al.*, 2006). Two broad philosophies have been generally pursued in the treatment and abatement of mine water pollution. These include measures directed towards prevention at source, ranging from monitored natural attenuation to physical intervention of one form or another, and measures directed at the resulting effluent, including active or passive remedial systems (Nyavor *et al.*, 1996; Younger, 2004; Johnson and Hallberg, 2005; Akcil and Koldas, 2006).

The Rhodes BioSURE Process is one among a range of mine water treatment technologies (MWTT) that have been developed to address specific aspects of the problem (Rose *et al.*, 1998; Whittington-Jones, 2000; Ristow *et al.*, 2002, Rose 2002, Whittington-Jones *et al.*, 2002, Rose *et al.*, 2003 and Ristow *et al.*, 2004). See Water Research Commission reports TT 195/03 and TT 196/02. The further scale-up development of this system, from earlier laboratory-based studies at Rhodes and Cape Town Universities, was undertaken in order to provide the groundwork for evaluation of the system and its progress to a full-scale industrial process. This research and development undertaking forms the subject of the current Water Research Commission report.

However, although both the mining industry and the related statutory/regulatory authority in South Africa share public commitment to the overarching principles of sustainability in the treatment of mine waters, no systematic mechanism has emerged to direct the application of sustainability thinking as a guiding principle in the research and development undertaking, nor in the selection and application of mine water treatment technologies by the industry decision-maker. Up to this time the application of sustainability principles in this area has been managed largely on an intuitive and *ad hoc* basis.

This study thus first undertook the development of a Sustainability Indicator Framework in order to provide a systematic basis for the incorporation of sustainability objectives in the MWTT bioprocess development operation. Then the Framework was used as an input to inform the investigation of the scale-up development of the Rhodes BioSURE Process. This is considered to be a novel contribution to the field.

2. DEVELOPMENT OF THE SUSTAINABILITY INDICATOR FRAMEWORK

In the development of the MWTT Sustainability Indicator Framework, an initial survey of industry thinking in this area was undertaken and, based on these outcomes, a detailed questionnaire methodology was developed in order to identify and quantify critical sustainability indicators. This included analysis of environmental, economic, social and technical indicators used in sustainability accounting practice in the industry. Statutory/regulatory sustainability targets in the same categories were derived from State of the Environment Reports (SoER) from Provincial authorities where mining is undertaken in South Africa. A synthesis of industry and SoER values was derived from weighted averages and the Sustainability Indicator Framework based on these outcomes. A Conceptual Decision-Support System, to guide the selection and development of MWTTs, was proposed and also based on these results.

In the development of the Rhodes BioSURE Process the use of primary sludge (PS) had been investigated as a potential carbon and electron donor source in the biological sulphate reduction reaction. In this regard the utility operator, and sewage treatment process infrastructure, was identified as potentially meeting aspects of the sustainability objectives identified for MWTT application development. However, novel reactor systems design had characterized the earlier research (Corbett, 2001). It was evident that equipment in common use in the hands of the sewage utility operator would be an important requirement where process sustainability was to be achieved and maintained over the many years over which the treatment of mine waters would be required. Both the Sustainability Indicator Framework and the Conceptual Decision-Support System thus provided inputs in the formulation of the experimental programme relating to the scale-up development of the Rhodes BioSURE Process.

3. BENCH- PILOT- AND TECHNICAL-SCALE STUDIES

Based on the above outcomes, a series of single- and multi-stage reactor configuration optimisation studies were undertaken at bench-, pilot- and technical-scale in order to provide design inputs in the development of the full-scale process. These studies were undertaken at the Environmental Biotechnology Research Unit at Rhodes University in Grahamstown, and at the ERWAT Ancor Works in Springs. Here a 2.4 km pipeline was constructed from the Grootvlei Mine in order to deliver mine water to the technical scale plant.

Three reactor configurations were investigated including the Stirred Tank Reactor (STR), the upflow Recycling Sludge Bed Column Reactor (RSBRc), and the RSBR configured to operate in Dortmund tank structures. These units were operated at hydraulic retention times (HRT) ranging between 22 to 72 hours and at chemical oxygen demand to sulphate ratios (COD:SO_4) ranging between 1:1 to 2:1. Studies undertaken in fed-batch, bench-scale reactors confirmed the preliminary feasibility of using established sewage treatment infrastructure as a replacement for novel reactor configurations that had been used in the initial studies. The results further indicated that the hydrolysis of PS occurred at different rates under biosulphidogenic conditions in the different reactor configurations investigated.

Scale-up of these findings in multi-stage pilot- (7.4 m^3) and technical-scale plants (680 m^3) showed comparable performances between the unit operations in terms of SO_4 and COD removal. These results indicated no apparent advantages in the uncoupling of hydrolysis and sulphate reduction in separate unit operations as had been suggested in previous studies. Scale-down/scale-up studies were undertaken in a continuously fed single-stage reactor configuration and showed that the process could be effectively operated in this way.

Previous proposals that chemical and biological gradients established in the sludge bed of the Recycling Sludge Bed Reactor (RSBR) exercised an influence on the rates of substrate hydrolysis were investigated and the relative activity of α- and β-glucosidase and protease enzymes was measured. Results provided additional support for this hypothesis and it was shown that enzyme assay may also provide a useful tool in process development and monitoring studies.

Sulphide recovery, following the sulphate reduction step in the BioSURE Process, was not investigated as a component of this study and detailed studies undertaken at EBRU are dealt with in WRC Report TT 197/07 "The Rhodes BioSURE Process, Part 3: Sulphur Production and Metal Removal Unit Operations". However, the treatment of final effluent or waste spills was identified as an important sustainability requirement given the toxicity of sulphide to human and ecosystem environments. A conventional trickle filter reactor system was evaluated for this purpose and showed close to 100% oxidation to sulphate in a short contact time operating regime. Although residual COD removal was low at ~20% of influent, it is considered that high rate recycle biofilter operation could achieve the COD discharge standard of 75 mg/ℓ.

4. CONCLUSIONS

This was a follow-up study to a number of previous Water Research Commission projects undertaken on the development of the Rhodes BioSURE Process and a number of conclusions emerged from the investigation:

- A systematic approach can be usefully applied in the identification of sustainability requirements to be incorporated in the development and assessment of MWTT. A Sustainability Indicator Framework methodology can be used in this regard;

- A Decision Support System provides a useful guideline in the implementation of the Sustainability Indicator Framework methodology;
- Sewage sludge provides a functional carbon and electron donor source in biological sulphate reduction in mine waste water treatment, and findings in earlier laboratory- and pilot-scale studies were confirmed at technical-scale;

- Reactor systems in common use in the hands of the utility operator, and sewage sludge can be used in operation of the Rhodes BioSURE Process for the treatment of mine drainage waste water;

- The upflow RSBR provides the optimal reactor configuration among those investigated;

- Enzyme activity analysis provides a useful tool in assessing the performance of the RSBR sludge bed;

- The biological trickle filter can be usefully applied in the polishing of final waters and in dealing with possible toxic spills from the process;

- Successful operation of the process a technical-scale provides a useful basis for proceeding to the full-scale implementation of the process in the treatment of mine drainage waste waters;

- The Rhodes BioSURE Process, as engineered within the context of the sewage utility operation, provides a basis for the long-term sustainability in the treatment of mine drainage wastewaters.

5. RECOMMENDATIONS

- The principal recommendation to emerge from this report was that sufficient data had been acquired to provide the conceptual framework for proceeding to the design of the full-scale Rhodes BioSURE Process plant at Ancor Works.

- The Sustainability Indicator Framework developed and described here is a first attempt at introducing a systematic approach in the incorporation of sustainability principles in the development, selection and implementation of mine water treatment technologies. Models such as these are refined through use and it is proposed that other applications of the system be undertaken in order to test the scope of its use and to add to and improve the concept.

6. RESEARCH PRODUCTS AND FOLLOW-UP ACTIONS

The results of the above studies provided inputs into the design, construction and commissioning of the first full-scale commercial application of the Rhodes BioSURE Process for mine wastewater treatment using sewage sludge as the carbon and electron donor source. The Grootvlei Mine and Ancor Works have been linked by pipeline and an operational capacity of 10 Mℓ/day water treated has been established with sulphate reduced from ~1300 mg/ℓ to <200 mg/ℓ. These developments constitute a novel contribution in the mine waste water treatment field.

The new full-scale plant was launched by Prof Dennis Goldberg at a ceremony at Ancor Works in May 2005.

ACKNOWLEDGMENTS

The authors wish to acknowledge with appreciation the financial support throughout the project of the WRC, BioPAD and ERWAT. A wide range of people and organisations have been involved in the provision of generous support, advice, encouragement and other inputs associated with the execution of this study.

- The previous Executive and Deputy Executive Directors of the WRC, Messrs. P Odendaal and D van der Merwe who have provided substantial advisory inputs, moral support and encouragement throughout;

- WRC Research Manager Mr Greg Steenveld whose enthusiasm and engagement with the progamme has added substantial value to the findings recorded here;

- BioPAD Management Mr Butana Mboniswa and Mr Delon Mudaly for their substantial support;

- Mr Roger Peter and Grahamstown Engineering Co. for sustained inventiveness in pilot plant construction. Mr Brian Ford and BJ Electrical for electrical and control elements;

- Management and staff at Grootvlei Mine and Springs Municipality;

- Erwat Water Care Company for supporting novel developments including Mr Arrie Korf, Mr Pat Twala, Mr Jurie Terblanche, Mr Koos Wilken, Dr Heidi Snyman, Mr Leon Naude, Mr Hannes Joubert and Mr Johan Cronje;

- Staff and students in the Department of Biochemistry and Microbiology and Rhodes University;

- Profs Geoff Hansford, Dick Loewenthal, George Ekama and Mark Wentzel, and Mr Neil Ristow at University of Cape Town. Prof Chris Buckley and Mr Chris Broeckaert at University of KwaZulu-Natal.

- The Project Team

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Mr W Pulles	Pulles, Howard & De Lange
Prof JR Duncan	Rhodes University
Prof PD Rose	Rhodes University
Dr OO Hart	Rhodes University

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ABBREVIATIONS

ABR: Anaerobic baffled reactor

AHP: Hierarchical analytic process

AII: Actual importance index

ALD: Anoxic line drains

AMD: Acid mine drainage

ANOVA: Analysis of variance

APHA: American Public Health Association

ASPAM: Algal sulphate reducing ponding process for acid metal wastewater treatment

BDET: 1, 3-benzenediamidoethanthiol dianion

BioPAD: Biotechnology Partnership for Development

CBA: Cost-benefit analysis

CEFIC: European Chemical Industry Council

cm: Centimetre

CoAsS: Cobaltite

COD: Chemical oxygen demand

CODs: Soluble chemical oxygen demand

CODt: Total chemical oxygen demand

CRA: Canadian Revenue Agency

CTSA: Cleaner Technologies Substitute Assessment

DEAT: Department of Environment and Tourism

DfE: Design for the Environment

DfS: Design for Sustainability

DPBR: Degrading Packed Bed Reactor

EBRU: Environmental Biotechnology Research Unit

EIA: Environmental impact assessment

EKC: Environmental Kuznets Curve

EMM: Ekurhuleni Metropolitan Municipality

EnTA; Environmental technology assessment

EPS: Extra-cellular polymeric substances

ERWAT: East Rand Water Care Company

FeAsS: Arsenopyrite

FeS: Pyrrhotite

FeS_2: Pyrite

GDW: Grahamstown disposal works

GYP-CIX: Ion exchange in fluidised bed

H_2CO_3: Hydrogen carbonate

HDS: High density sludge process

HRAP: High rate algal pond

HRT: Hydraulic retention time

H_2S: Hydrogen sulphide

IBL: Integrated Bottom Line

ImPACT: Impact (I) = population (P) x per capita GDP (A) x intensity of use (C) x efficiency of technology (T)

IMPI: Integrated Managed Passive Treatment System

IPAT: Impact (I) = population (P) x per capita affluence (A) x technology (T)

ITRC: Interstate Technology & Regulatory Council

IU/mℓ: Enzyme activity expressed as International Units per millilitre

ℓ: Litre

ℓ/hr: Litres per hour

LCA: Life cycle assessment

LCC: Life cycle cost analysis

m: Metre

M: Mole

MCA: Multi-criteria analysis

MEND: Mine Environment Neutral Drainage Program

mℓ: Millilitre

Mℓ: Mega litre

Mℓ/d: Mega litres per day

mℓ/min: Millilitre per minute

MPB: Methane producing bacteria

MPRD: Mineral and Petroleum Resources Directive

MPRDA: Mineral and Petroleum Resources Development Act

MSR: Multi-stage reactor

MUF: Methylumbelliferone

MWCPT: Mine water concentrate preparation tank

MWFT: Mine water feed tank
MWHT: Mine water holding tank
MWTT: Mine water treatment technology
Na_2BDET: Disodium salt of 1, 3-benzenediamidoethanthiol
Na_2SO_4: Sodium sulphate
NEMA: National Environmental Management Act
NiAsS: Gersdofite
OLC: Open limestone channels
PbS: Galena
PHD: Pulles Howard and De Lange
PIRAMID: Passive *in-situ* remediation of acidic mine / industrial drainage
PRB: Permeable reactive barriers
PS: Primary sludge
PVC: Polyvinyl chloride
RAPS: Reducing and alkalinity producing systems
RSBR: Recycling sludge bed Reactor
RSBRc: Upflow column recycling sludge bed reactor
RSBRd: Upflow Dortmund tank recycling sludge bed reactor
SAPS: Successive alkalinity producing systems
SFA: Substance flow analysis
SHT: Sludge holding tank
SIA: Social impact assessment
SO_4: Sulphate
SoER: State of the Environment Report
SPARRO: Slurry precipitation and recycle reverse osmosis
SRO: Seeded reverse osmosis
SRP: Sulphate reducing prokaryotes
STR: Continuous stirred tank reactor
TA: Technology assessment
TBL: Triple bottom line
TCA: Trichloroacetic acid
TRIS: Tris (hydroxymethyl) aminomethane
t/year: Ton per year
UASB: Upflow anaerobic sludge blanket

UNEP: United Nations Environmental Programme

UNEP/IETC: United Nations Environmental Program/International Environmental Technology Centre

USDA: United States Department of Agriculture

USEPA: United States Environmental Protection Agency

VDI: The German Institute for Engineers

VFA: Volatile fatty acids

WRC: Water Research Commission

1 SUSTAINABILITY AND MINE WATER TREATMENT

1.1 MINE WATER - SCOPE OF THE PROBLEM

The generation of mine water pollution, both during and after mining operations has characterised the industry worldwide since ancient times (Banks *et al.*, 1997; Brown *et al.*, 2002; Younger *et al.*, 2002; Luptakova and Kusnierova, 2005; Akcil and Koldas, 2006). In the case of acid mine drainage (AMD) waste waters the problem may persist for many decades to thousands of years (Nordström and Alpers, 1999; Kalin, 2001). These waters are generally characterised by reduced pH, elevated levels of a range of heavy metal contaminants, most notably iron, and salts such as sulphates and chlorides. The environmental consequences of mine water pollution have been comprehensively described (Lyew and Sheppard, 2001; Brown *et al.*, 2002; Younger *et al.*, 2002; Younger, 2004).

Where mining activities are associated with the exposure of pyrite (FeS_2) and other sulphide-containing minerals, their oxidation, which may be both chemically and microbiologically-mediated, has been identified as the main source of acid contamination in AMD generation (Johnson, 1995; Brown *et al.*, 2002; Cocos *et al.*, 2002; Johnson *et al.*, 2002; Costello, 2003; Akcil and Koldas, 2006). AMD generation can occur in underground mine workings, waste rock dumps, mill tailings piles, ore stockpiles, spent ore piles from heap leach operations and in other residue deposits which present a high surface area for oxidation (Bunce *et al.*, 2001). It should be noted, however, that not all mine water is characterised by low pH and may contain elevated concentrations of metals at near neutral or alkaline pH values (Younger, 2004).

The importance of mine water pollution is predicated on its potential negative human health impacts and financial and environmental risks and liabilities. Globally, estimates of the impacts and the extent of the problem on various water resources have been reported for a number of regions. For example, estimates by the United States of America's Bureau of Mines indicate that over 19,000 km of rivers and streams, and 73,000 hectares of lakes and reservoirs are negatively impacted by mine water from abandoned coal and metal mines (Brown *et al.*, 2002). The total length of watercourses negatively impacted by mine water in Europe exceeds 5000 km (Younger, 2004). In the United Kingdom, an accidental discharge of 54 Mℓ of highly acidic metal-contaminated mine water into the Carnon River, from the Wheal Jane Mine in Cornwall, affected approximately 6.5 million square meters of receiving waters, with peak zinc and cadmium concentrations reaching 540 mg/ℓ and 600 mg/ℓ respectively (Brown *et al.*, 2002). Younger (1994) further reported the discharge of metal contaminated mine water from the Lower Ynysarwed Colliery into the Neath Canal in the United Kingdom, which covered the canal bed with ochre and denuded all forms of aquatic life over a stretch of 12 km.

The financial burden associated with mine water pollution is often considerable. In Pennsylvania, for example, the cost of reclamation of watersheds impacted by mine water was estimated at \$15 billion (Rossman *et al.*, 1997). The mine water liability associated with existing Canadian mine tailings and waste rock is estimated to be between \$2 billion and \$5 billion (Feasby and Tremblay, 1995 cited in Price and Errington, 1998; Brown *et al.*, 2002).

Although no comprehensive study has been undertaken on the extent of the overall impact of the mine water problem in South Africa, the limited information available suggests that the problem is also substantial. In the Witwatersrand Gold Mining region of South Africa, pyrite was identified as the most abundant of 70 ore minerals (Feather and Koen, 1975 cited in Naicker *et al*., 2003). Other common sulphur-containing ore minerals identified in the region included arsenopyrite (FeAsS), cobaltite (CoAsS), galena (PbS), pyrrhotite (FeS) and gersdofite (NiAsS) (Naicker *et al.*, 2003). In the 1980s, approximately 120×10^6 t/year of ore, 30×10^6 t/year of mined-out waste rock and about 90×10^6 t/year of low-grade sand dumps and slimes, all containing substantial quantities of pyrite and a number of other sulphidic ores, were being milled and processed or reprocessed. Pulles *et al.* (1996) reported that this resulted in the discharge of approximately 440 Mℓ/day of highly polluted mine water into the surface and ground water resources in South Africa. The Vaal River alone, which supplies a significant proportion of the water requirements of the Gauteng Province, was estimated to receive approximately 400,000 tons of salts from this source annually (Funke *et al.*, 1991).

The impacts of mine water pollution on biological systems are mostly severe. Elliot *et al.* (1998) have observed that the consequence of acidity and heavy metal contamination in aquatic and terrestrial ecosystems is a reduction in both species diversity and the total biomass composition of such systems. Bell *et al.* (2001) studied a coal mine in South Africa abandoned in 1947 and found that by 1996 the mine was still discharging AMD into an adjoining river resulting in sulphate content in excess of 1000 mg/ℓ and pH < 3.2. This has resulted in severe adverse effects on vegetation in the surrounding area, with approximately three hectares almost completely denuded and the near total destruction of aquatic life in the seepage area. Naicker *et al.* (2003) have reported that the ground waters and the upper 20 cm of soil profiles in close proximity to the water table within the mining areas of the Witwatersrand region were heavily polluted, being characterised by low pH and high concentrations of metals. Furthermore, they observed that polluted groundwater in the region contributed approximately 20% of stream discharge, leading to the acidification of stream water in the region. Impacts on the environment of the decanting of large volumes of mine waters expected from the East Rand Mines in the Gauteng Province have been described by Scott (1995). The discharge is expected to rise to > 70 Mℓ/day after final closure of these mines.

The statutory approach to mine water pollution in South Africa has followed an integrated approach to environmental management (DEAT, 2000). Environmental legislation developed in this regard includes the White Paper on Integrated Pollution and Waste Management in South Africa (DEAT, 2000), the National Water Act 36 of 1998, the National Environmental Management Act 107 of 1998 (NEMA) (Section 28 and 30), the Mineral and Petroleum Resources Development Act 28 of 2002 (MPRDA) (Sections 38, 41, 43, 45 and 46) and the Mineral and Petroleum Resources Development Regulations (MPRD Regulations) (GNR 527 in GG 26275 of 23 April 2004) (Bosman and Cotzé, 2005). These lay emphasis on several key principles including environmental accountability, wastewater discharge standards, the polluter-pays and sustainability considerations.

Sustainability principles which incorporate responsibility for mining and minerals industry operations have been formulated in the Berlin Guidelines (Hinde, 2000; United Nations, 2002a), and, in South Africa, by the King II Report on Corporate Governance (Institute of Directors in Southern Africa, 2002) and the Johannesburg Stock Exchange Socially Responsible Investment Index (Johannesburg Stock Exchange, 2005). The triple bottom line (TBL) basis of sustainability accounting, which incorporates environmental, social and economic components of sustainability, has generally been adopted by the mining industry in South Africa (Elkington, 1988; McNeill, 2000; Gibson, 2001).

As a result of these developments, which have characterised the mining industry worldwide, the sustainability of mine water treatment technologies (MWTTs) has emerged as a critical factor in the choice-of-technology decision-making process (Johnson and Hallberg, 2005). The long time frame over which treatment of mine water is expected to be required underscores not only the TBL sustainability accounting components of the technology development process, but also the technical sustainability of the actual technologies developed. However, what has emerged in the study reported here is that little direction appears to be available to guide the incorporation of sustainability considerations within the technology development process, and no formalised systemic decision-support system is in general use by the mining industry to select from a range of alternative technologies. Although a substantial technological response has been invested in the mine water problem over many years, and the importance of sustainability is widely acknowledged, this appears to have largely been undertaken with the incorporation of sustainability principles in the technology development process managed on *ad hoc* basis.

1.2 THE TREATMENT OF MINE WATER

Development of cost-effective and sustainable remediation solutions for the mine water problem has been the subject of extensive review (Brown *et al.*, 2002; Diels *et al.*, 2002; Gibert *et al.*, 2002; Younger *et al.*, 2002; Bowell, 2004; Johnson and Hallberg, 2005; Kalin *et al.*, 2006; Zagury *et al.*, 2006). In addition to monitored natural attenuation, the two broad philosophies which have been pursued in the treatment and abatement of mine water pollution include measures directed towards prevention at source, usually involving physical intervention of one form or another, and measures directed at the resulting effluent, including active or passive remedial systems (Nyavor *et al.*, 1996; Younger, 2004; Johnson and Hallberg, 2005; Akcil and Koldas, 2006). Active treatment systems have been characterised by Younger (2004) as those systems that make use of conventional wastewater treatment processes, require ongoing inputs of electrical energy and/or chemical reagents in a controlled process. Furthermore, these systems require frequent operator attention and usually involve three typical steps in the treatment process, namely oxidation, dosing with alkali and accelerated sedimentation and, where necessary, include desalination processes.

Passive treatment has been defined by the PIRAMID Consortium (2003) and PHD (2002) as that which utilises naturally available energy sources such as topographical gradient, microbial metabolic energy, photosynthesis and chemical energy and requires regular but infrequent maintenance to operate successfully over its design life.

Both active and passive systems may be implemented using physicochemical or biological treatment technologies (Pulles *et al.*, 1996). Developments in these areas are reviewed below.

1.2.1 Physicochemical Treatment

1.2.1.1 Passive Physicochemical Treatment Systems

Treatment systems that use limestone to neutralise AMD such as anoxic lime drains (ALDs) (Turner and McCoy, 1990; Hedin and Watzlaf, 1994; Hedin, 1997), open limestone channels (OLCs) and diversion wells (Arnold, 1991; Ziemkiewicz, 1997; Cravlotta III, 2003) have been widely exploited as they are relatively cheap to construct and maintain (Cravotta III and Trahan, 1999).

ALDs are designed as buried trenches filled with limestone through which the AMD is channeled. These are usually not designed as stand-alone passive systems, but usually precede a constructed wetland or a settling pond or other structures that may facilitate the precipitation and settling of metal hydroxides (Hedin, 1997; Hudnall, 2003). The major effect on AMD when passed through a correctly operating ALD is an increase in pH, bicarbonate alkalinity and calcium concentrations (Hedin, 1997). ALDs exhibit large variations in alkalinity generation and metal precipitation (Faulkner and Skousen, 1993), which has been attributed to the different chemical compositions of the influent mine water (Hedin *et al.* 1994). Hedin and Watzlaf (1994) examined the performance of 21 ALDs and found that in all the systems studied, the variation in alkalinity generation was less than that of acidity removed. It was also concluded that the concentration of alkalinity generated in the ALDs peaked after 14-23 hours of retention time with no marked increase in alkalinity thereafter. Concern has been expressed at the potential failure or poor functionality of ALDs at pH <5, with the armouring of limestone and bed clogging occurring in the absence of anoxic conditions (Faulkner and Skousen, 1994 cited in Hudnall, 2003; Pulles *et al.*, 1996).

OLCs make use of open channels that are lined with coarse limestone (Hudnall, 2003). In these systems, AMD is treated when the limestone dissolves, introducing alkalinity and, with increasing pH, precipitation of metal hydroxides results (Ziemkiewicz, 1997). Limestone Sands treatment systems involve the use of sand-sized limestone particles to treat AMD-impacted streams and other water bodies (Faulkner and Skousen, 1994 cited in Hudnall, 2003). The limestone is fed into the affected stream at various points and has been used to treat many impacted streams and rivers in Western Virginia (Hudnall, 2003). Price and Errington (1998) suggested that the successful long-term operation of AMD mitigation measures must be designed, constructed and operated in a manner that provides for indefinite performance. This requires sustained vigilance and regular monitoring to identify possible upset conditions (Price and Errington, 1998). Without frequent control, the long-term successful performance of most passive treatment systems has largely been a matter of conjecture (Pulles *et al.*, 1996).

1.2.1.2 Active Physicochemical Treatment Systems

Chemical treatment methods involve the addition of basic chemicals such as lime, soda ash, caustic soda and ammonia to neutralise acidity and enhance metal hydroxide formation (Bosman, 1983; Thompson, 1986; Pulles *et al*., 1996; Hedin, 1997). Mechanical devices such as aerators and mixers, and chemical additives such as oxidisers and coagulants are frequently employed to improve the rates of chemical reactions and sludge settling (Hedin, 1997). The Savmin process employs a multi-stage operation in treating AMD including heavy metal and magnesium precipitation, gypsum de-supersaturation, ettringite precipitation for elimination of calcium and sulphate, carbonation and the recycling of aluminium hydroxide (Ramsay, 1998). A novel treatment method, in which heavy metals are precipitated with lime and coupled with a sulphide-carrier magnetic separation system, has also been reported (Feng *et al*., 2000). Neutralisation is generally effective in the elimination of metal contaminants in AMD, but ineffective in sulphate removal (Maree *et al*., 1992). The precipitation of sulphates with barium has been investigated and deemed economically unfeasible, except in instances where the barium can be recovered and recycled (WRC, 1991).

Other active physical treatment technologies have been drawn from metallurgical processing methodologies and may be extremely valuable where the recovery and re-use of metals is economically viable (Younger, 2004). Matlock *et al*. (2002) demonstrated that 1, 3-benzenediamidoethanthiol dianion (BDET) can selectively and irreversibly precipitate heavy metals from AMD with efficiencies exceeding 90%. Hart *et al*. (1987) described a number of membrane, chemical oxidation and thermal adsorption technologies and their application in the desalination of different categories of industrial wastewaters with high saline loads. Pulles *et al*. (1996) described instances where membrane technologies and their variants such as seeded reverse osmosis (SRO), slurry precipitation and recycle reverse osmosis (SPARRO), low pressure reverse osmosis, and other non-membrane technologies such as ion exchange, ion exchange in a fluidised bed (GYP-CIX) and freeze desalination have been applied to treat AMD in South Africa. Critical problems associated with the use of all membrane applications, are scaling, fouling of membranes and inefficient sulphate removal. However, the SPARRO process was able to yield high quality gypsum as a value-added by-product with minimal quantities of brines requiring disposal (Chamber of Mines Research Organisation, 1988; Lorax Environmental, 2003).

The high capital, operational and management costs, the technical expertise and complexities generally associated with the deployment of physicochemical treatment technologies, and also long-term sustainability concerns have led to an increased focus on the potential of biological treatment options, which have been perceived as potentially more cost-effective, simpler, and possibly more environmentally sustainable (Rose, pers. com. 2006).

1.2.2 Biological Treatment

Biological treatment research and development has also focused on both passive and active treatment operations, and depend on the ability of strictly anaerobic, dissimilatory sulphate reducing prokaryotes (SRP) to reduce sulphate to sulphide by oxidising an electron donor source, usually organic carbon (Rose *et al.*, 1998; Gibert *et al.*, 2004). While reduction of sulphate by SRP is seen as the primary activity in this group, they have recently also been shown to be involved in a range of other metabolic activities such as metal and oxygen reduction, metal methylation and dymethylation, organic fermentations, sulphur disproportionation, and the utilisation of sulphur in a variety of intermediate redox states (Hines *et al.*, 1997).

The biology of the SRP has been the subject of extensive review (Postgate, 1984; Gibson, 1990; Widdel and Bak, 1991; Widdel and Hansen, 1992; Odom and Singleton, 1993; Barton, 1995). Most SRP function optimally at pH values between 6 and 7, at temperatures of approximately 30^{o}C and in predominantly anaerobic environments (Widdel, 1998). However, studies have demonstrated their presence in anoxic microenvironments in aerobic wastewater remediation plants (Lens *et al*., 1995a), also in the oxic/anoxic interface in aerated circum-neutral pH waters (Johnson and Hallberg, 2003) and in both extremely (pH <3) and hyper acidic (pH <1.3) environments (Johnson, 1995; Johnson and Hallberg, 2003). Eliot *et al.* (1998) demonstrated the ability of SRP to withstand pH 3.0 with some level of sulphate reduction. Recent advances in the development of solid media and the use of molecular techniques in the study of AMD have necessitated a reassessment of the microbial diversity of SRP (Johnson and Hallberg, 2003). Previously unreported groups involved in chemical transformations have been identified in different categories of AMD wastewaters (Hallberg and Johnson, 2001).

It is generally accepted that, under prevailing anaerobic conditions, SRP reduce sulphates to sulphides in a dissimilatory mode, and in the process, generate alkalinity, which is valuable in increasing the pH of the solution(**Equation 1**) (Kim *et al.*, 2003).

$$2CH_2O + SO_4^{2-} \longleftrightarrow 2HCO_3^- + H_2S \qquad (1)$$

Depending on the pH of the reaction medium and the solubility of the metals that are present, the resultant hydrogen sulphide reacts with heavy metals to form insoluble metal sulphide precipitates (Hammack *et al.*, 1992).

A critical factor constraining the above process is the supply of organic materials including the carbon and electron donor sources (Rose *et al.*, 1998). A variety of simple organic substances have been shown to be efficient carbon and electron donor sources in biological sulphate reduction, such as molasses (Maree and Hill, 1989), ethanol and methanol (Postgate, 1984; Braun and Stolp, 1985; Tsukamoto and Miller, 1999), lactate and cheese whey (Oleszkiewicz and Hilton, 1986; Herrera *et al.*, 1991; Christensen *et al.*, 1996), producer gas (Du Preez *et al.*, 1992; Du Preez and Maree, 1994; van Houten *et al.*, 1994; van Houten *et al.*, 1996; Maree *et al.*, 2001) and poly(lactic acid) (Edenborn, 2004). However, the use of these substrates in large scale AMD bioremediation processes is restricted by the high costs involved (Whittington-Jones, 2000). A number of researchers have sought to ameliorate this limitation through the evaluation of other abundantly available and less costly complex organic matter such as peat, hay, straw, sawdust (Kalin *et al.*, 1991), cattle waste (Ueki *et al.*, 1988), algal biomass, tannery effluents (Boshoff *et al.*, 1996; Dunn, 1998), sewage sludge (Butlin *et al.*, 1956; Burgess and Wood, 1961; Pipes, 1961; Conradie and Grutz, 1973; Molepane, 1999; Whittington-Jones, 2000; Corbett, 2001; Enongene, 2003), oak chips, sludge from wastepaper recycling plant, spent mushroom compost and organic-rich soil (Chang *et al.*, 2000). In recent chemical characterisation studies of four organic substrates (compost, sheep and poultry manure, and oak leaf), Gibert *et al.* (2004) demonstrated a correlation between the lignin content of complex organic substrates and their rates of biodegradability and sulphate reduction. It was found that lower amounts of lignin present in the organic substrates supported higher biodegradability and a higher potential to support bacterial activity. Roman (2005) showed that lignocellulose can be used as a carbon source for sulphate reduction. His research demonstrated enhanced lignocellulose biodegradation under biosulphidogenic conditions by a sulphate reducing microbial consortium. Under sulphidic conditions, the bonds within the lignin macromolecule are cleaved by cellulolytic enzymes most probably derived from *Clostridia sp.* (Roman, 2005).

1.2.2.1 Passive Biological Treatment Systems

Various forms of passive biological treatment are used in the remediation of AMD wastewaters (MEND, 1999; Costello, 2003). It should be noted however, that some passive treatment systems also integrate aspects of both physicochemical and biological treatment technologies. Examples of such integrated treatment systems include among others, mixed compost/limestone systems, permeable reactive barriers (PRBs) and successive alkaline producing systems (SAPS) (MEND, 1999; Younger *et al.*, 2002; Costello, 2003; Kalin, 2004b).

The concept of wetlands as a technology applied in the treatment of AMD was pioneered in the United States of America and is loosely based on a set of assumptions about water chemistry, engineering principles and ecological function (Cairns and Atkinson, 1994; Hedin *et al.*, 1994). Tuttle *et al.* (1969) observed a decrease in acidity and metal concentrations when AMD was fed through sawdust or naturally occurring wetlands. Huntsmann *et al.* (1978), and Wieder and Lang (1982), also observed improved water quality associated with the flow of AMD through natural wetlands. Initially, macrophytes, bryophytes and algae were thought to contribute in various ways in increasing the pH and the uptake of metals in wetland systems. However, in a subsequent wetland study, it was observed that increases in pH and metal uptake resulting from microbially-mediated reactions are of importance in the remediation process (Johnson, 1995).

In aerobic surface-flow wetlands, the AMD flows to depths of between 10 and 50 cm and heavy metals are precipitated as oxides and hydroxides, while in the anaerobic compost sub-surface flow wetland, flows mimic saturated groundwater systems and metals precipitate as metal sulphides (Younger, 1995). In the latter, the water flows through an approximately 30 to 40 cm thick wetland substrate, made up of a variety of organic-rich materials, which may include peat, hay, straw, sawdust (Kalin *et al.*, 1991), spent mushroom compost, straw bales and a combination of manure and sawdust (Younger *et al*., 1997). The resulting anoxic conditions and the readily available carbon in the substrate stimulate SRP growth, thereby effecting microbial sulphate reduction, the generation of sulphide and alkalinity, and the precipitation of heavy metals which accumulate in the substrate (Younger, 1995). It has been observed that where low pH and high metal concentrations prevail, a combination of lime treatment and wetlands is required for satisfactory results (Gazea *et al*., 1996). While this passive technology has gained popularity as a “walk away” solution for the mining industry, as it provides a low operational cost to the long-term management of the AMD problem, certain weaknesses have been identified in its application. These include limitations such as large surface area needs for high AMD flows. In addition, sceptics question the long-term stability and the diffuse spread of deposited metals (Rose *et al.*, 1998). McGinness *et al.* (1997) has described the use of wetlands in the treatment of AMD as a “black box technology, not entirely under control”.

The PRB is a passive treatment system consisting of a special barrier made up of reactive material designed to target and remove specific contaminants from polluted streams flowing through it (Blowes *et al.*, 2000; Gavaskar and Reeter, 2000; ITRC, 2003; Kalin, 2004b). The reactive material in PRB systems designed to treat AMD with metal contamination is usually made of solid organic materials such as compost, wood chips or sawdust (Blowes *et al.*, 2000), which enable the growth of SRP. The successful operation of a PRB system is limited by several factors which include the depletion of the chemical component of the reactive barrier, which leads to the slowing of chemical reactions in the system and physical clogging of the reactive barrier with time (Blowes *et al.*, 2000; ITRC, 2003).

The SAPS, also including reducing and alkalinity producing systems (RAPS) have the following basic indicators: an organic mulch layer, a limestone layer and a drainage system, with the majority of them also including a flushing system (MEND, 1999). In these systems, AMD flows into the top of the SAPS reactor, creating a water layer that prevents the penetration of oxygen into the bottom layers. The organic layer facilitates the removal of dissolved oxygen from the water and the anaerobic conditions which develop at increasing depths within the system become conducive for the establishment of SRP (MEND, 1999).

Biosorption treatments for the removal of metals are involved in passive treatment technologies although they are also frequently encountered in nature (MEND, 1999). It should be noted however, that some authors have also considered biosorption systems as an active biological treatment (Brown *et al.*, 2002). These systems rely on the absorption or adsorption of metal ions from solution to a biological material such as bacteria, algae, fungi and yeast by ion exchange, complex formation and precipitation in living or non-living cells (Gadd, 1992; Schultze-Lam *et al.*, 1993; MEND, 1999; Brown *et al.*, 2002). Research into biosorption has focused on the use of materials such as waste biomass (Mattuschka and Straube, 1993), algal biomass (Kratochvil and Volesky, 1998) and filamentous bacteria (Shuttleworth and Unz, 1993). Canty *et al.* (2000) reported the use of proprietary cultures of microorganisms immobilised on a porous ceramic medium to remove cyanide, nitrate and metals from mine process water at pilot-scale. Although the use of biological materials for adsorption of contaminants is relatively inexpensive, it mostly cannot be re-used, thereby posing a potential waste disposal problem (Brown *et al.*, 2002).

Passive biological treatment systems have been thought to hold promise for the post-closure phase of mine operation. However, their requirement for large expanses of land (USDA, 1995; ITRC, 2003; Halverson, 2004), the technical challenges associated with the long-term management of wastes within these systems (PIRAMID Consortium, 2003), poor and inconsistent sulphate removal generally estimated at between 10 and 30% in the literature (Pulles *et al.*, 2001; ITRC, 2003; Lorax Environmental, 2003) and the decline and severely reduced performance with time (Heath, 2000; Pulles *et al.*, 2001) are seen as major constraints in their exploitation.

In order to improve the performance of passive biological treatment systems, Pulles Howard and De Lange (PHD), a consultancy firm based in Johannesburg, South Africa, in collaboration with the Environmental Biotechnology Research Unit (EBRU) at Rhodes University (Grahamstown, South Africa), have developed a hybrid passive treatment technology known as the Integrated Managed Passive System (IMPI) (PHD, 2002; Molwantwa *et al.*, 2003). In a Department of Arts, Culture, Science and Technology (DACST) [now known as the Department of Science and Technology (DST)] Innovation Fund study, Roman (2005) showed that the initial performance of lignocellulose packed bed systems was linked to the mobilisation of readily extractable soluble organic carbon from the substrate which was made available for use by SRP for sulphate reduction. This leaves the core lignocellulose structure with a depleted source of soluble organic carbon and hence resulting in the onset of the performance decline seen in these systems after several months of operation (Pulles *et al.*, 2001). Follow-up studies designed to unravel the progression of carbon source utilisation in the system provided evidence that carbon-carbon, glycosidic and ether linkages of lignin were cleaved under biosulphidogenic conditions and a descriptive model of lignocellulose degradation was proposed to explain the events occurring within the system (Roman, 2005).

The results obtained from the above study informed the development of the Packed Bed Degrading Reactor (DPBR), a unit within the IMPI system, in which long-term sulphate reduction could be sustained by poising initial conditions in the reactor (Molwantwa *et al.*, 2003). In the course of process development over a period of four years, an 800% improvement in reactor performance was reported for the DPBR (Molwantwa *et al.*, 2003). However, the treatment of large volume flows of AMD in the IMPI system is seen as a potential constraint in use of the technology.

Active biological treatment systems, which require continuous direct intervention in their operations, offer performance advantages over passive biological treatment systems and are reviewed in the following section.

1.2.2.2 Active Biological Treatment Systems

Active biological treatment systems may be defined as biology-based treatments that exploit the remediation capability of microorganisms in bioreactors and as such offer greater control than is feasible within a passive treatment environment (Brown *et al.*, 2002). Various studies investigating different aspects of the use of SRP in active biological AMD treatment systems have been reported. Duc *et al.* (1998) and Chang *et al.* (2000) investigated the selection of suitable substrates for SRP activity. The revitalisation of a spent organic substrate in bioreactors was investigated by Tsukamoto and Miller (1999). The ability of anaerobic bioreactors to function in acidic conditions (Elliot *et al.*, 1998) and studies attempting the modelling of sulphate reduction in bioreactors have also been reported (Ristow, 1999; Drury, 2000; Ristow *et al.*, 2002). Greben *et al.* (2004) investigated COD/SO_4 ratios using propionate and acetate as energy source for the biological reduction of sulphate in AMD. Koschorreck *et al.* (2004) investigated the accumulation and inhibitory effects of acetate in a sulphate reducing reactor. Johnson *et al.* (2004) reported an integrated biological treatment system which incorporated different populations of acidophilic and acid-tolerant SRP in on-line bioreactors. This system selectively removed copper and zinc from AMD while maintaining low pH to retain iron in solution (Johnson *et al.*, 2004). Investigations to quantify the rate of sulphate reduction and precipitation of heavy metals have also been reported (Ueki *et al.*, 1991; Kar *et al.*, 1992; Machemer and Wildeman, 1992).

SRP have a relatively poor adhesion capability (Isa *et al.*, 1986), which has rendered stirred tank reactor configurations, traditionally used for the digestion of sewage sludge (Toerien and Maree, 1987) generally unsuitable for large scale AMD remediation. A number of improved bioreactor designs have, however, been shown to successfully retain SRP, including the up-flow anaerobic sludge blanket (UASB)(Barnes *et al.*, 1991; Lens *et al.*, 1998), anaerobic baffled reactor (ABR) (Barber and Stuckey, 1999), upflow packed bed reactors (Maree *et al.*, 1991; Colleran *et al.*, 1998), granular sludge bed (Omil *et al.*, 1996), anaerobic filter bioreactor (Lens *et al.*, 1995a), multi-stage reversing-flow bioreactor (Takahashi and Kyosai, 1988), sequencing batch reactors (Herrera *et al.*, 1991), fluidised bed systems (Umita *et al.*, 1988), and the recycling sludge bed reactor (RSBR) (Whittington-Jones, 2000; Corbett, 2001; Enongene, 2003).

In sulphidogenic systems, research has shown that a number of variables affect the kinetics of the system and therefore the outcome of the process. These include the ability of the SRP to compete with methane producing bacteria (MPB) for the available organic substrate (Visser, 1995; Shin *et al.*, 1996; Omil *et al.*, 1998) and the sensitivity of the bacteria to toxic levels of sulphide (Oude Elferink *et al.*, 1994; Visser, 1995; Omil *et al.*, 1996), the organic electron donor to sulphate ratio which impacts on the competition between SRP and MB (Oude Elferink *et al.*, 1994; Bhattacharya *et al.*, 1996), the type of substrate in the system i.e. acetate (Oude Elferink *et al.*, 1994; Maillecheruvu and Parkin, 1996) or hydrogen (Kristjansson *et al.*, 1982), the concentration of undissociated volatile fatty acids (VFA) (Reis *et al.*, 1990), pH (Visser, 1995) and hydrogen partial pressure (Costello *et al.*, 1991). Despite the advances made in understanding SRP and their role in the remediation of AMD, and in the development of the assortment of SRP reactor configurations discussed above, only a limited number of reports of successful full-scale implementations of active biological SRP-mediated remediation processes have been published. These include an SRP process remediating polluted groundwater using the Thiopaq process (Scheeren *et al.*, 1993; Boonstra *et al.*, 1999; Picavet *et al.*, 2003; Benschop *et al.*, 2004); the Biosulphide process, which integrates a chemical/biological process designed to treat metal-contaminated, sulphate-rich wastewater

(Rowley *et al.*, 1997; Brown *et al.*, 2002); the use of an integrated algal-SRP process for the treatment of tannery effluents in Wellington, South Africa (Dunn, 1988; Rose *et al.*, 1998), the CSIROSURE process, which utilises ethanol as a carbon source to treat AMD (Lorax Environmental, 2003; Greben *et al.*, 2005) and a process treating citric acid-production wastewater (Colleran *et al.*, 1998).

The development of most active biological wastewater remediation systems have largely been based on high-cost bioreactors and expensive carbon sources (Johnson, 2003). However, it has been recommended that truly sustainable solutions for the remediation of AMD wastewater pollution should be based on their effectiveness on appropriate time scales (Kalin, 2004a). The long-term sustainability of treatment systems based on high-cost bioreactors and expensive carbon sources therefore requires further attention.

1.3 THE RHODES BioSURE PROCESS

As the search for simple, efficient, cost-effective and sustainable remediation technologies is largely driven by environmental factors (and now increasingly by broader sustainability criteria), the linkage of AMD and sanitation wastewater treatment has been proposed as a potential treatment strategy (Rose *et al.*, 2002). The linkage of mine water treatment and the utility operator not only offers substantial potential cost reductions in the carbon and electron donor source for the biological sulphate reduction reaction but also places the sustainability of the treatment in the hands of the operator most likely to function successfully over the time frames involved. In this context, the Rhodes BioSURE Process has been developed at bench-scale and 40 m^3 pilot-scale at EBRU, Rhodes University, and utilises primary sludge (PS) as the sole carbon source for biological sulphate reduction (Rose *et al.*, 2002).

The initial investigation of complex carbon utilisation as an effective electron donor in biological sulphate reduction process development was based on the observation of enhanced degradation of particulate organic wastes in sulphate reducing tannery ponding environment (Rose *et al.*, 1998). Boshoff *et al.* (1996) and Dunn (1998) had recorded efficient sulphate reduction, with concomitant high degrees of solubilisation and utilisation of organic matter and associated metal precipitation in these systems. These observations had suggested the potential use of ponding systems, and particularly their anaerobic compartments, as bioreactors for the treatment of AMD on a large scale. This led to the subsequent development of the Integrated Algal Sulphate Reducing Ponding Process for Acid Metal Wastewater Treatment (ASPAM process) at EBRU, Rhodes University (Rose *et al.*, 1998; Rose, 2002). Degradation of complex organic substrates had been observed to be associated with sulphide gradients in the tannery pond investigation and it had been proposed that recycling of particulate organic matter through the sulphide gradients in the pond water column may contribute to the enhanced degradation effect observed. Further supporting data was acquired when the pond inlet pipe was relocated to feed into the base of the pond (Rose *et al.*, 1998).

In follow-up studies, Molepane (1999) successfully demonstrated the feasibility of employing PS as an electron donor source for biological sulphate reduction in a 1 m^3 stirred tank reactor. Whittington-Jones (2000) used a downflow RSBR (**Figure 1.1a**) to simulate and unravel the mechanism underpinning enhanced particulate organic matter degradation during the up-welling effect observed in the sulphidogenic tannery ponding environment (**Figure 1.1b**) and a multi-stage reactor (MSR) (**Figure 1.2**) was developed to investigate the role of solubilisation and hydrolysis of complex organic carbon sources in this system (Whittington-Jones, 2000). The results obtained previously by Boshoff *et al.* (1996), Dunn (1998), Molepane (1999) and Whittington-Jones (2000), suggested that enhanced degradation of particulate organic substrates was linked to enhanced enzyme activity and, subsequently, the accelerated hydrolysis of these compounds to small molecular weight fatty acids which were utilised in sulphate reduction. These findings led in turn to the bench-scale studies of what became known as the Rhodes BioSURE Process.

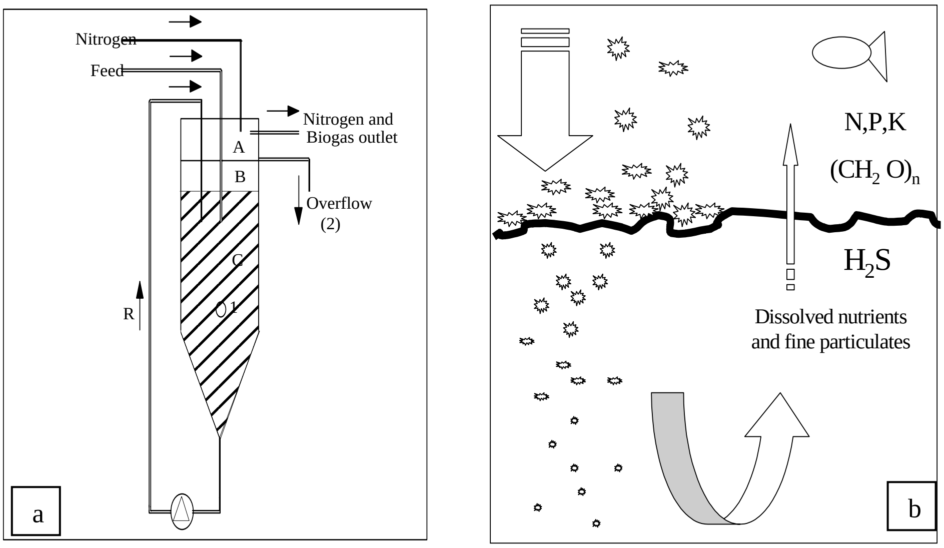

Figure 1.1 (a) The 1L prototype Recycling Sludge Bed Reactor used to simulate the breakdown of particulate organic matter in natural sulphidogenic settlement and sedimenting processes shown in (b). In the Recycling Sludge Bed Reactor, the degrading sludge is returned via line R to blend with the incoming feed (After Whittington-Jones, 2000).

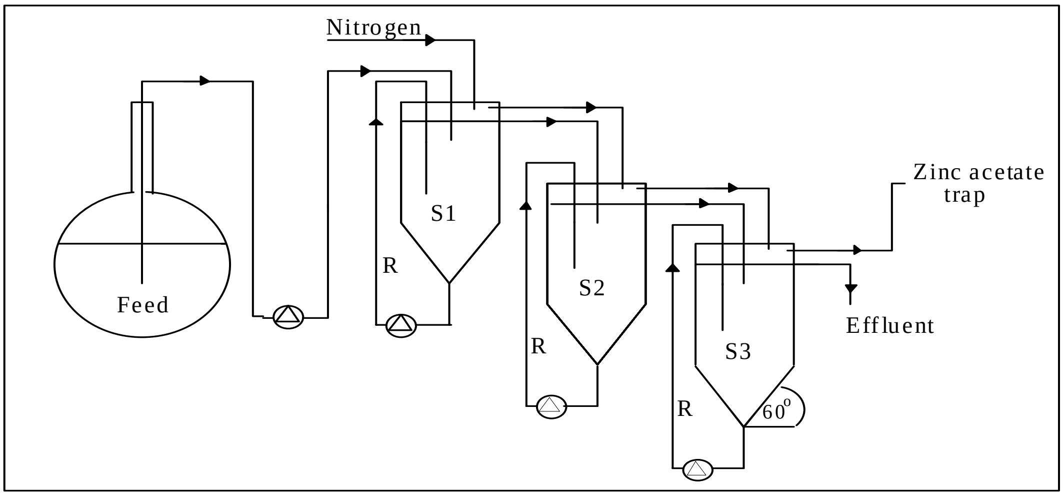

Figure 1.2 The multi-stage Recycling Sludge Bed Reactor used to investigate the solubilisation of primary sludge as an electron donor source in sulphate reduction activity. Effluent is passed though three consecutive Recycling Sludge Bed Reactors (After Whittington-Jones, 2000).

1.3.1 The Rhodes BioSURE Process in the Treatment of AMD

Following bench-scale studies of the enhanced hydrolysis operation, the process was scaled-up to a 40 m^3 pilot plant (Corbett, 2001) located on site at Grootvlei Mine, treating an AMD stream with a sulphate load around 2000 mg/ℓ (Figure 1.3). This pilot plant was configured as a multi-stage process, consisting of three unit operations, the hydrolysis unit, the sulphate reduction unit and a polishing unit for treating the final effluent. The hydrolysis unit was configured as a RSBR (R1 in Figure 1.4), and catered for separate optimisation of the hydrolysis of complex organic matter such as PS. In this reactor design, AMD and PS were fed from the top of the reactor and the particulate organic matter in the PS settled into the falling sludge bed at the base of the unit, where liquefaction of the particulate organic matter, the commencement of sulphate reduction, and the accumulation of sulphide and alkalinity were observed.

Figure 1.3 The Rhodes BioSURE Process Pilot plant located at Grootlvei Gold Mine No 3 Shaft in Springs.

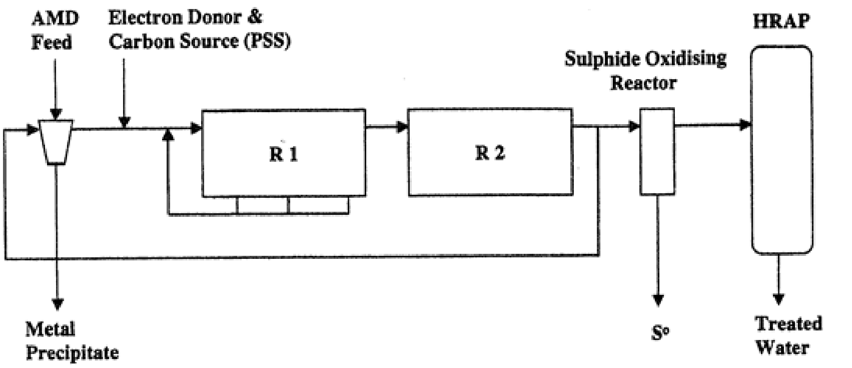

Figure 1.4 Process flow diagram of the Rhodes BioSURE Process applied to the treatment of Acid Mine Drainage (AMD). R1= Recycling Sludge Bed Reactor, R2=Baffled Reactor; HRAP=High Rate Algal Pond; PS= Primary sludge. A side stream of sulphide rich water is blended with incoming mine water to precipitate heavy metals in the feed. Sulphur production may be effected by sulphide oxidation and removal (Rose *et al.*, 2002).

The sludge was drawn down the bed at the bottom of the RSBR and recycled to blend with the influent mixture of AMD and PS, simulating the upwelling effects described earlier. In addition, fresh organic substrate being introduced into the system was entrapped within the bacterial flocs and coupled with residual, and as yet undegraded, settleable solids and was subjected to further rounds of recycling (Corbett, 2001). The liquid stream, which at this stage was enriched with the solubilised particulate organic fraction, passed to a baffled reactor (R2) where the major fraction of sulphate reduction occurred using the up-flow characteristics of the UASB-type reactors, with biomass retention in each compartment. In the pilot operations, water from R2 was discharged via a final polishing step, which in this case was effected by a High Rate Algal Pond (HRAP). Corbett (2001) reported 67% sulphate removal and 72% chemical oxygen demand (COD) removal, with the major fraction of COD removal occurring in the RSBR, and of sulphate reduction in the ABR. Furthermore, around 98% of settleable COD was removed in the RSBR.

Having developed the Rhodes BioSURE Process at 40 m^3 pilot-scale, the need was identified to undertake the integration and verification of the various research outcomes as a functional entity at technical-scale. This would be a necessary precursor to full-scale commercial application. However, in approaching the planning and design of the process scale-up, which will be described further in this study, it was considered essential that this be informed, and possibly even driven by technology sustainability considerations. This was considered necessary in order to meet legislative/regulatory requirements and also TBL sustainability reporting constraints imposed by policy considerations of the mining companies themselves.

1.4 SUSTAINABLE TECHNOLOGY DEVELOPMENT

One of the most widely quoted definitions of sustainable development is that of the Brundtland Commission (World Commission on Environment and Development, 1987) which states that it is “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs”. The World Commission in 1987 was the culmination of events which began with increasing environmental awareness in wealthy industrial societies commencing in the 1960s (Jischa, 1998; Jischa, 1993 cited in Tulbure, 2002). One of the first structured management responses was the emergence of the technology assessment concept in the United States of America and its subsequent spread to Europe (Jischa, 1998). Other important developments included the publication in 1972 of the seminal report “The Limits to Growth” by the Club of Rome (Meadows *et al.*, 1972; Jischa, 1998); the expansion of the sustainability debate leading to the publication of the “Global 2000 Report for President Carter” (Barney, 1980; Jischa, 1998; Barney, 2000).

In 1992, the United Nation’s Earth Summit held in Rio de Janeiro, Brazil, developed “Agenda 21” as a blue print for the implementation of sustainable development objectives (Jischa, 1998; United Nations, 1992). More recently, the Johannesburg Conference on Sustainable Development and the Environment has sought to consolidate the implementation of the commitments of the Rio Conference through its Plan of Implementation (United Nations, 2002b). The TBL concept of sustainability accounting has taken this further and places a high premium on not only environmental components of sustainable development but also on social and economic indicators (Elkington, 1988; McNeill, 2000; Gibson, 2001). These indicators have been identified as the pillars of sustainable development, each playing an equally important role in the successful implementation of truly sustainable development initiatives (Svanström *et al.*, 2004). It should, however, also be noted that technical sustainability indicators have more recently been proposed as the fourth dimension of the sustainable development concept. This has been applied in the developing country context with specific applications in dealing with the importation of foreign technologies (Dunmade, 2002). In this study, the phrase Integrated Bottom Line (IBL) sustainability indicators has been adopted for use in lieu of TBL in order to account not only for the traditional TBL parameters but also other parameters such as technical and legal indicators

In an operational context, technology may be defined as "the final step in the research process that starts with basic research, which pursues the discovery of facts about nature, and is followed by applied research, which employs knowledge gained through research to realise some social good"(Menkes, 1979). The relationship between technology and the environment is a complex one in which technology paradoxically constitutes the prime source of, and solution for, environmental problems (Huesemann, 2001). This relationship is further elucidated in concepts such as the IPAT model (Fischer-Kowalski and Amann, 2001), the ImPACT model, an adaptation from the IPAT model by Waggoner and Ausubel (Taylor, 2002) and the Environmental Kuznets Curve (EKC) originally conceptualised by Simon Kuznets (Fischer-Kowalski and Amann, 2001; Lindmark, 2002; Yandle *et al.*, 2004). In broad terms, these models postulate that the use of dirty technologies may increase negative environmental impacts while improvements and the responsible application of clean technology will inevitably result in the minimisation of the impacts on the environment. The use of cleaner technologies is, therefore, one of the critical factors that may lead not only to environmental improvement but also an accompanying increase in economic growth (Munsinghe, 1999; Lindmark, 2002). This is known as the *technique effect* of growth on the environment in which technological advancements, which arise with economic growth, as affluent countries invest more in research and development, generally lead to the substitution of rudimentary, obsolete and dirty technologies with cleaner ones, thereby improving the quality of the environment (Borghesi, 1999). Carraro and Galeotti (2004) have noted that today, technical change is overwhelmingly recognised as the primary catalyst to solutions for environmental problems. The need to correlate the technology development process with environmental sustainability thinking becomes critical if technology output is to meet sustainable environmental requirements.

The World Commission on Environment and Development (1987) has recognised that in meeting the objectives of sustainable development, the availability, development or implementation of appropriate technology, in conjunction with adequate laws and policies, and a proper institutional framework are indispensable conditions that have to be met. Furthermore, the Plan of Implementation (United Nations, 2002b) reiterated the significance of the transfer and diffusion of environmentally responsible technologies in collaboration with other traditional environmental management tools as a collective strategy in the attainment of a more sustainable development path. Sustainable development therefore demands responsible planning of technological development given that the unrestricted use of natural resources, and the concomitant pollution of the environment through unregulated and improper use of technology, pose serious problems (CEFIC, 1997) that may undermine the attainment of sustainable development.

The environmental impacts of mine water and the likely time scale over which the problem is expected to persist have been well documented (Scott, 1995; Younger, 1997; Kalin, 2001). However, short-term economic interests have continued to propel technological innovations to implementation by businesses that would generally be construed as "meaningless or even negative" within the confines of sustainable development (Seghezzo, 2004). As a concept, sustainability assessment (Balkema *et al.*, 2002; Dunmade, 2002; Pope *et al.*, 2004) comprises a number of indicators aligned with the principles of the IBL approach to sustainable development. It strives to account for the widest possible range of impacts on society and the environment as a result of the adoption and use of a system, concept or technology (Seghezzo, 2004). According to Pope *et al.* (2004), sustainability assessment constitutes "the process by which the implications of an initiative on sustainability are evaluated, where the initiative can be a proposed or existing policy, plan, programme, project, piece of legislation or a current practice or activity". This may contribute significantly towards the attainment of sustainable development objectives in the bioprocess development research arena and in the exploitation of MWTTs in the mine water treatment industry. Sustainability assessment as applied to technology development, assessment, selection, and adoption in general and in the MWTT research and development community and industry, therefore deserves more attention.

Nijkamp and Vreeker (2000) and Dunmade (2002) stated that the concept of sustainability may be context-specific and be propelled by the specific needs and opportunities in a given location. In line with this philosophy, Pope *et al.* (2004) has proposed the concept of 'assessment for sustainability" which involves a clarification of what constitutes sustainability and the development of corresponding criteria against which an assessment can be performed. In South Africa, national policy objectives such as the White Paper on Integrated Pollution and Waste Management (DEAT, 2000) and a host of environmental legislation are aimed at ensuring, amongst other outcomes, social equity and responsible environmental stewardship. The concept of context-specificity of sustainability with particular reference to technology development and adoption was therefore considered particularly important in the present study. It was expected that the needs and opportunities within the mining industry in South Africa, the target operational environment for the technology being developed, would largely influence the sustainability of the final technology output.

The mining industry in South Africa exhibits a variety of unique characteristics embodied within a variable spatial and temporal context (Chamber of Mines, 2001; Cranville, 2002). For example, sustainable development in the mining industry is commonly construed to be equivalent to sustainable mining. This is considered in the context of the declining economic importance of mining in the South African economy which has been exacerbated by a number of factors including the high cost of capital resulting from high interest rates, tax rates and currency volatility, high cost of labour per unit output, high cost of logistics and poor efficiency in the use of cheap electricity (Chamber of Mines, 2001). Furthermore, mines are usually located in very remote and disparate geographical settings, and ultimately results in the establishment of human settlements, usually consisting of different cultures interacting with each other and that depend on the mines for their livelihood and sustenance. As mining resources are finite, retrenchments and mine closures are inevitable (Cranville, 2002). This may translate into reduced or limited funding during post-closure, which impacts negatively not only on the livelihood of the surrounding communities, but also on the capacity of the mines to meet their commitments towards their environmental responsibilities, especially the long-term treatment of mine water. These factors have a direct bearing on the exceptionally long period of time required for mine water treatment, and by implication, on the development, selection and application of any given MWTT. This spatial and temporal uniqueness reinforced the incentive to develop a specific tool to guide the development of potential MWTTs during the design phase, and the selection of the most applicable MWTT from a suite of alternatives that could be sustainable within such a setting. In the development, assessment, adoption and application of MWTTs, it is vital that these unique characteristics be borne in mind, if such interventions are to be sustainable, given the long time frame over which the problem is anticipated to persist.

A review of the literature showed that no sustainability guidelines or decision-support systems have been specifically developed to guide the development of MWTTs towards the attainment of desired sustainability outcomes of the mining industry. It emerged that at this time mainly intuition and the gut feel of researchers and managers constitute the main reference that is generally used in the development, scale-up and application of MWTTs. It has been astutely observed that “when the desire to innovate outstrips the ability to assess and absorb the risks” new risks arise during the technology development process (Smith, 1992 cited in Hellström, 2003). A need was therefore noted for the development of a structured framework for MWTTs assessment based on the most relevant sustainability indicators in any given context, and the IBL indicators, that could be applied at the various stages of the bioprocess development undertaking and in the evaluation and selection of competitive MWTTs for adoption in the mining industry.

1.4.1 Bioprocess Development and Scale-up

Despite successful completion of the ongoing studies of the Rhodes BioSURE Process noted above, commercial process failure may still result where the process goals are not shaped and informed by the operating environment in which it will need to perform (Rose pers. com, 2006). Although the above research provided important pointers as to bioreactor and process reconfiguration studies needed in the scale-up procedure, little guidance was available to direct the integration of this undertaking with sustainability thinking, the basic paradigm on which the whole research undertaking had been based from the outset. It has been noted that new research efforts geared towards the full understanding of wastewater treatment systems and their integration in environmental management objectives need to take full account of the scientific, technical, environmental, social and economic perspectives that impact on their operation (Hellström *et al.*, 2000; Balkema *et al.*, 2002). Technology development and implementation therefore needs to be pursued holistically in order to meet these requirements.

The scale-up of bioprocesses has been comprehensively reviewed by Junker (2004). According to Ju and Chase (1992), the scale-up of bioprocesses proceeds through three stages: laboratory-scale, where fundamental concept testing through basic studies is undertaken; pilot-scale, where the process is optimised, and plant or production-scale where the process is developed economically. It should, however, be noted that other terms such as shake-flask scale, bench-scale, technical-scale, semi-production scale, full-scale, commercial-scale and industrial-scale abound in the literature and have been used to describe the above stages or variants thereof. In the present study, the pilot-scale definition according to Ju and Chase (1992) was adopted while technical-scale was considered to be synonymous with semi-production scale. Furthermore, the scale-up process is generally carried out through one of four approaches namely fundamental methods, semi-fundamental methods, dimensional methods and rules of thumb (Kossen and Oosterhuis, 1985; Oosterhuis *et al.*, 1985). The exact methodology employed is largely dependent on process conditions and the availability of preliminary data that may indicate whether the procedure selected is applicable (Banks, 1979 cited in Junker, 2004). Guidelines for the inclusion of sustainability requirements are, however, generally lacking in these approaches. Up to the pilot-scale stage of the investigations, the development process is aimed primarily at obtaining the desired process outputs i.e. acquiring an understanding of the biology and proof of concept (Whittington-Jones pers. com, 2006). During the initial investigations leading up to the pilot-scale trials, limited or no attention is generally paid to the sustainability of the concept being investigated. Pilot-scale studies may therefore provide a unique opportunity to intervene, investigate and improve the sustainability of the concept being developed.

The Canadian Revenue Agency, CRA (2004) defined a pilot plant as a “non-commercial scale plant in which processing steps are systematically investigated under conditions simulating a full production unit; the primary purpose of the pilot plant being to obtain engineering and other data needed to evaluate hypotheses, write product or process formulae, establish finished product technical specifications, or design special equipment and structures required by a new or improved fabrication process". Leo Baekeland (of "Bakelite" phenol/formaldehyde resin fame) had noted, "Commit your blunders on a small scale and make your profits on a large sale" (Griskey, 1979). In the context of sustainable technology development, a pilot-scale study may also provide an opportunity for the consolidation of sustainability issues, as it offers a unique avenue to introduce certain changes to the process before proceeding to full or commercial scale. For example, avenues for the reduction or substitution of raw materials and for reduction in energy consumption could be explored, while different process configurations may be investigated with the objective of improving on technical efficiency, effectiveness and even on costs. This is feasible as the selection of the final design from a range of alternatives could be guided by sustainability principles through the application of relevant environmental management tools.

1.5 TOOLS OF SUSTAINABLE TECHNOLOGY DEVELOPMENT

While there is no gainsaying that the impacts of technology on the environment are multifaceted and very complex, the use of appropriate environmental management tools may contribute substantially towards understanding technological interactions with the environment and the attainment of desired sustainability outcomes in technology development and process scale-up undertakings. Conceptual schemes that depict a generic technology development cycle (Coates, 1998), and technology interaction with the environment (Balkema *et al.*, 2002), provide a basis for identifying and anticipating first order socio-economic and biophysical environmental impacts, from which higher order impacts could be deciphered. While there are a number of environmental management tools available, their usefulness in accentuating the TBL indicators in the technology development process is rather limited as most of these tools do not underline the IBL indicators during the technology development process. Instead, they focus largely on the evaluations of the final technological products on a comparative basis. A synopsis of some of the more widely used of the environmental tools is presented in **Table 1.1**.

The development of technology both influences and is influenced by the social, economic and cultural setting in which the technologies develop (Kemp, 2000), in addition to the environmental and technical settings in which the technologies develop and are exploited. It is recognised that in practice, the process of developing a product or process that excels on environmental grounds, while remaining economically and technically competitive is a particularly challenging objective (Pujari *et al.*, 2004). It is now widely accepted that there is no "silver bullet" environmental tool, programme or policy which provides a "one-size-fits-all" solution for all environmental, social, economic and technical problems (Finnveden, 2000). In developing and assessing technologies, an overarching instrument should be considered that is flexible enough to be modified to integrate other tools or components thereof, and by so doing, potentially account for the broad factors mentioned above. Most of the currently available environmental management tools are largely comparative in nature and are focused on evaluating and selecting the most appropriate technology from a range of alternatives. These are briefly reviewed below.

Table 1.1 Environmental tools that have been used in the assessment and application of technologies.

Environmental Tool	Overview of Tool
Cleaner Technologies Substitute Assessment (CTSA)	A comparative assessment of a number of processes based on factors such as comparative risk, competitiveness on performance and costs, and contributions to resource conservation (USEPA, 1998; USEPA, 2001)
Environmental Technology Assessment (EnTA)	Assesses implications of a technology and guides choices of technology. Centres on implications for health, safety and wellbeing, and for natural resources and ecosystems; costs of technology intervention and monetary benefits (Coenen, 1996; UNEP/IETC, 1998; Coates, 1998; Hay and Noonan, 2000; Hoskim, 2001).
Analytic Hierarchical Process (AHP)	A decision approach designed to aid in the solution of complex multiple criteria problems in a number of application domains. The decision-maker judges the importance of each criterion in pair-wise comparisons (Saaty, 1980; Saaty, 2000; Atthirawong, 2002; Linkov *et al.*, 2004)
Multi-Criteria Analysis (MCA)	A structured system for ranking alternatives and making selections and decisions (Dalal-Clayton, 1993; Fatta *et al.*, 2003; Seghezzo, 2004; Seghezzo *et al.*, 2004; Linkov *et al.*, 2004).
Environmental Life Cycle Assessment (LCA)	Evaluates the environmental impacts associated with a product, process or activity explicitly over the entire life cycle (Moberg, 1999; Hay and Noonan, 2000; Friedrich and Buckley, 2002; Fatta *et al.*, 2003; Rydh, 2003; Hertwich, 2005)
Life Cycle Cost Analysis (LCC)	Assesses costs of a product or service from a life cycle perspective and may also include environmental and social costs (White *et al.*, 1996; Moberg, 1999)
Environmental Auditing	Creates awareness of environmental problems by highlighting direct environmental impacts (Moberg, 1999; Fatta *et al.*, 2003)
Environmental Impact Assessment (EIA)	Identifies and predicts the environmental impacts of a project, policy or similar initiative and provides a basis for decision on the acceptability of the likely impacts (Hay and Noonan, 2000; Fatta *et al.*, 2003)
Cost-Benefit Analysis (CBA)	Measures net contribution of a project or public policy to the economic wellbeing of members of society (Dalal-Clayton, 1993; Moberg, 1999; Seghezzo, 2004; Seghezzo *et al.*, 2004; Linkov *et al.*, 2004)
Environmental Risk Assessment	Evaluates and compares risks to the environment and public health in order to determine the environmental consequences of an initiative under consideration (Moberg, 1999; Hay and Noonan, 2000; Fatta *et al.*, 2003)
Social Impact Assessment (SIA)	Highlights social aspects associated with a particular development, location or environmental problem. Fosters dialog with surrounding communities and interested and affected parties (Dalal-Clayton, 1993; Fatta *et al.*, 2003)
Emergy Analysis	Uses energetic basis for quantification or valuation of ecosystems goods and services (Odum, 1996; Moberg, 1999; Hau and Bakhi, 2004)
Exergy Analysis	Analysis and improvement of the efficiency of chemical and thermal processes or technologies; may include LCA and sustainability assessment of industrial products and services (Finnveden and Östlund, 1997; Moberg, 1999; Balkema *et al.*, 2002; Hau and Bakshi, 2003)
Technology Assessment (TA)	Systematically examines the effects on society that may occur when a technology is introduced, extended or modified (Dalal-Clayton, 1993; CEFIC, 1997; Hill, 1997; Coates, 1998; Coates, 2001; UNEP, 2001).
Substance Flow Analysis (SFA)	Assessment of a single substance or a group of substances that is associated with specific environmental effects (van der Voet 2002; ConAccount, 2003; Rydh, 2003)
Environmental Simulation Models	Software tools used in addressing issues relating to environmental management and technology; stores and elaborates environmental data in order to provide conclusions on future trends or evaluation of alternative scenarios (Fatta *et al.*, 2003)
	Elementary datum or a simple combination of data capable of measuring an observed phenomenon; enhance communication about the environment and aid in policy formulation and decision-making (Fatta *et al.*, 2003)
Design for the Environment (DfE)	Systematically integrates environmental considerations into product and process design (Ashley, 1993; Billatos and Basaly, 1997; De Medonca and Baxter, 2001; Canada National Research Council, 2003; Harper and Graedel, 2004)

Of the tools described in **Table 1.1**, environmental life cycle assessment (LCA), has found wide scale application in the water treatment industry, with studies that examined wastewater treatment plants using LCA principles being reported by Zhang and Wilson (2000), Tillman *et al.* (1998) and Emmerson *et al.* (1995). Other studies involving the use of LCA methods have been reported for the assessment of the disposal and reuse of sewage sludge resulting from wastewater treatment processes (Bridle and Skrypski-Mantele, 2000) and in the assessment and selection of potable water treatment processes (Friedrich and Buckley, 2002).

LCA is credited as being the “only tool which has a cradle-to-grave approach” (Friedrich and Buckley, 2002). By considering all the inputs and outputs of a system, LCA facilitates the estimation of environmental impacts in a systematic and scientific manner and makes it possible for two technologies performing the same function to be judged on environmental grounds (Friedrich and Buckley, 2002). However, in this system, no rigorous focus is attached to the social, economic and technical aspects of the evaluation, as it is believed that LCA “cannot cover all issues and or every part of complex industrial systems” (Friedrich and Buckley, 2002).

In addition to extensive data requirements, the dearth of data, missing data, poor data quality and value preferences have been cited as some of its major shortcomings (Friedrich and Buckley, 2002; Fatta *et al.*, 2003; Rydh, 2003). LCA was also found to be difficult to use by standard sanitary engineers employed in municipalities in Norway due to its perceived complexity (Lindholm and Nordeide, 2000). The general paucity of quantitative data in developing countries in particular makes the effective use of LCA in these regions questionable (Seghezzo, 2004).

By contrast, conventional technology assessment (TA) is based on a traditional analytical approach that seeks to “speak truth to the power”, in other words, telling it like it is (Klüver *et al.*, 2000). The German Institute for Engineers, through its VDI-Guideline 3780, defines TA as “the methodical, systematic and organised process of analysing a technology and its developmental possibilities; assessing the direct and indirect technical, economic, health, ecological, human, social and other impacts of this technology; judging these impacts according to defined goals and values, or demanding further desirable development; deriving possibilities for action and design from this and elaborating these, so that well-founded decisions are possible and can be made and implemented by suitable institutions if need be” (VDI, 2000 cited in Tulbure, 2002). It is a “powerful strategy with which to generate the appropriate technologies necessary to achieve any sustainable development” (Ludwig, 1998). It should be noted that while a multiplicity of perspectives (van Eijndhoven, 1997; La Porte, 1997; Coates, 1998), paradigms and dilemmas (van Eijndhoven, 1997), approaches and types (Schot and Trip, 1996; van Den Ende *et al.*, 1998; Coates, 2001), shortcomings (van Eijndhoven, 1997; Assefa *et al.*, 2005), methodologies and tools (La Porte, 1997; van Eijndhoven, 1998; Porter *et al.*, 2004), functions (Smit and Leiten, 1991, cited in van Eijndhoven, 1997) and possible outcomes of TA (Coates, 2001) have been documented, it remains a versatile and an overarching tool through which sustainable development may be operationalised. It is a tool that may potentially accentuate the environmental, social, economic and technical impacts in the evaluation of technologies, on account of being able to synthesize other environmental management tools including LCA, and EIA (Ludwig, 1998). However, TA has traditionally been used as a post-script diagnostic tool in the evaluation of technologies and not much attention has been paid to its potential use as a tool that may inform and drive the direction of the new technology development decision-making process.

Environmental technology assessment (EnTA) is a relatively new environmental management tool developed and promoted under the auspices of the United Nations Environmental

Program (UNEP) (UNEP/IETC, 1997; Hoskim, 2001). It is largely a policy support tool that uses qualitative and exploratory techniques in a practical and structured approach to analyse the consequences of, and the alternatives to a proposed technology investment (Hay and Noonan, 2000). EnTA uses concepts and procedures in line with the need to reflect diverse human values, expert opinion and incomplete information and understanding (Hay and Noonan, 2000). While it may be applied to different applications and approaches such as treatments, adaptation and innovation, participants at workshops organised to promote its use held in Johannesburg, South Africa and in Manila, The Philippines, noted that the tool focuses and emphasises environmental outcomes, is subjective in nature, lacks a specific weighting procedure for aggregating impacts and explicit acknowledgement of uncertainties (Hay and Noonan, 2000). Like conventional TA, EnTA is largely a post-script comparative evaluation tool and its possible role in the technology development process has not been elaborated.

The cleaner technologies substitute assessment (CTSA), a form of TA, was developed under the auspices of the United States Environmental Protection Agency (USEPA) Design for the Environment (DfE) program. The CTSA methodology provides a systematic means of evaluating risks to human health and the environment, in addition to the performance, costs, and natural resource use of traditional and alternative technologies. It is an information seeking tool that makes detailed information available so that businesses can make their own decisions (USEPA, 2006). It is also largely a comparative tool, but can aid technology development.

The concept of Design for the Environment (DfE) embodies a paradigm shift in which design methodologies for environmental improvement predicated on a ‘cradle to grave’ foundation are encouraged (Billatos and Basaly, 1997). It is the systematic integration of environmental considerations into product and process design (Canada National Research Council, 2003) which treats a product’s environmentally preferable attributes which may include recyclability, disassembly, maintainability, and refurbishability as design objectives rather than as constraints (Ashley, 1993). It is thought to be the most widespread and promising tool for environmental responsiveness for manufacturers, designers and engineers (DeMendonca and Baxter, 2001).

DfE deviates from the other environmental management tools discussed above in that it provides an opportunity for the examination of the environmental soundness of a product over its entire life cycle by introducing changes or modifications early in the product design process (De Medonca and Baxter, 2001; Harper and Graedel, 2004). The Canadian National Research Council (2003) proposed the following steps that may be applied in tandem or modified to suit specific needs in the pursuit of DfE projects: creating a design brief, analysing the product’s environmental profile, analysing internal and external drivers, analysing improvement options and studying option feasibility. Additionally, the Canadian National Research Council (2003) proffers numerous strategies through which DfE projects may be operationalised. These strategies include for example the integration of product functions, the optimisation of production functions, the facilitation of easy maintenance and repair of the product, physical optimisation of the product, the use of cleaner materials, and the use of renewable materials, among others. As a tool, DfE is applicable in new product/process development and in the improvement of an existing product/process (Canadian National Research Council, 2003).

Using a fundamental DfE approach such as in-depth end-users’ needs analysis, broad sustainability criteria that include economic, social, environmental, legal and technical indicators may be developed and used to introduce changes that promote economic, social, environmental and technical sustainability in the early design stage of bioprocess development. This would promote not only the environmental sustainability but the overall sustainability of the technology being developed, especially within specific contexts. This may be construed as "Design for Sustainability" (DfS), whereby industry-specific sustainability needs with relevance to the research and development, assessment and selection of a technology are identified and integrated into the design process.

1.6 THE PROBLEM

While early technology development had been guided by relatively simple criteria such as intuition or even blind guesses and then followed by proof of concept, the contemporary technology development environment is characterised by new constraints. One such constraint is the performance of the final technology output in terms of sustainability considerations. Given its all-encompassing nature, and the different articulations of the concept of sustainable development (World Commission on Environment and Development, 1987; Mitchum, 1995; Tijmes and Luijf, 1995), it is expected that different role players in the MWTT process research, development and application field may promote different indicators of the concept to suit a particular objective. From a statutory/regulatory perspective, the focus on sustainability may be on social and environmental criteria, compared to a business perspective, which may largely focus on economic criteria and to the technology developers' perspective, which may largely focus on technical considerations. These various views raise the question of what actually constitutes sustainability in a particular context as far as the research and development, selection and application of MWTTs is concerned and how the research and development process may be guided to meet the identified sustainability objectives.

In undertaking the scale-up development of the Rhodes BioSURE Process as an active MWTT within the constraints of the contemporary technology development environment, there was therefore a requirement to focus on the sustainability component of the technology. A review of the literature and extensive engagement with many stakeholders in the MWTT research and development field revealed that no dedicated decision-support tools were known that could enable the synthesis of the sustainability criteria from the above-mentioned perspectives in order to guide the research, development, selection and application of water treatment technologies in general and of MWTTs in particular.

1.7 RESEARCH HYPOTHESIS

The scale-up undertaking in bioprocess development of MWTTs provides an opportunity to improve the sustainability component of these technologies using context-specific sustainability criteria.

1.8 RESEARCH OBJECTIVES

The research program described here was undertaken to pursue the development of the Rhodes BioSURE Process at technical-scale, which had evolved through a range of bench-scale and 40 m^3 pilot-scale studies undertaken by EBRU (Rhodes University) and other collaborators over a period of some years. In addition, a need for decision support guidelines in this undertaking specifically, and applied to sustainability requirements for the development of a new water treatment technology generally, was identified. The study was therefore directed towards the following objectives:

1. To identify how decisions on the evaluation and selection of MWTTs are conducted within the mining industry in South Africa;
2. To investigate and develop improvements to the decision-making framework for MWTTs evaluation and selection based on sound sustainable development principles;
3. To identify key sustainability indicators that would be required to guide and inform procedures for the scale-up of the Rhodes BioSURE Process, and
4. To investigate the scale-up development of the Rhodes BioSURE Process and to provide the design criteria necessary for its application at commercial-scale.

2 A SUSTAINABILITY INDICATOR FRAMEWORK FOR GUIDING THE ASSESSMENT AND DEVELOPMENT OF MINE WASTEWATER TREATMENT TECHNOLOGIES

2.1 INTRODUCTION

Environmental managers, technologists, engineers and consultants, policymakers and other stakeholders in the mining industry are required to make decisions on MWTTs which have far-reaching implications for their companies, clients and governments. Azapagic (2004) has noted that the sustainability challenges confronting the mining and minerals industry are some of the most complex facing any industrial sector. Many initiatives are, therefore, being pursued globally to tackle sustainable development issues in the mining and minerals industry. These initiatives are driven by a number of factors including national and international legislation, enhancement of shareholder value and long-term commercial survival, improved management of risk, improved relationships with local communities and improved standing with governments and regulators (PricewaterhouseCoopers, 2001; Azapagic, 2004).

In meeting these objectives, the use of sustainability indicators has emerged as a verifiable process by which company performance could be monitored and by which sustainability reporting and stakeholder engagement (Warhurst, 2002; Azapagic, 2004) could be facilitated. Sustainability indicators have already been applied in the assessment of water and assessment of waste water treatment systems (Larsen and Gujer, 1997; Hellström *et al.*, 2000; Hoffman *et al.*, 2000; Morrison *et al.*, 2001; Balkema *et al.*, 2002; Foxon *et al.*, 2002; Larsen and Lienert, 2003; Kvarnström *et al.*, 2004; Bracken, 2005). Other methods such as economic analysis (Balkema *et al.*, 2002), LCA (Bengtsson *et al.*, 1997), exergy (Hellström and Kärrman, 1997), emergy (Björklund, 2000), and general systems analysis (Hellström *et al.*, 2000; Balkema *et al.*, 2002) have also been proposed for use in sustainability assessment of technologies in the water industry. However, much of this work has been context-specific (Hoffman *et al.*, 2000) and determined by the needs and opportunities in a given location (Nijkamp and Vreeker, 2000). Pope *et al.* (2004) have proposed the concept of 'assessment for sustainability' which seeks to clarify what constitutes sustainability and to develop corresponding criteria against which an assessment could be performed. The development of a structured methodology for the identification of the most relevant sustainability indicators within any given context appears to be less well considered, certainly in the mine water treatment field. Also little attention appears to have focused on the development of quantitative weights for the identified sustainability indicators in mine water treatment technology assessment. It was therefore considered necessary to first develop a structured Sustainability Indicator Framework that would enable the identification of the most relevant sustainability indicators in the mining industry in South Africa where the deployment of water treatment technology was anticipated, and then to apply quantitative weights for the identified sustainability indicators. This would be necessary in order to align the technology development project towards meeting industry sustainability objectives in general and the identified sustainability targets for specific technologies such as the Rhodes BioSURE Process in particular. In meeting the above requirements, the objectives of commercial mining operations and the statutory/regulatory agencies would need to be effectively integrated.

In considering the mining industry's inputs into the development of the proposed Sustainability Indicator Framework, two phases in the life of a mine, which may potentially influence the decision-making process in the selection and deployment of MWTTs need to be considered. The first phase, which may be identified as the active mining or operational phase is more often than not associated with resource-intensive wastewater treatment engineering and is characterised by the allocation of generous financial, intellectual, human and technical resources commensurate with the profit-making mining operation. The second phase, identified as the post-operational or post-closure phase, involves installations with often limited resources allocated for mine wastewater treatment.

The post-closure mine wastewater pollution problem is often combined with a deprived socio-economic environment that replaces the once vibrant mining operation in the post-closure phase, resulting in a technologically-constrained environment due to ageing infrastructure, skills/job losses and closure of ancillary industries (Aitchison, 2001 cited in Nel *et al.*, 2003; Nel *et al.*, 2003). Although financial resources would have been set aside for the purpose of mine wastewater treatment during the post-closure phase, it is unlikely that the overall resource support base that characterises treatment systems during active mining would be maintained at comparable operational levels, and over the appropriate time scales involved. The prevailing circumstances that characterise the above phases may be substantially worse off when evaluated in a developing country context compared to a developed country context.

Thus, need was identified to develop a generic approach for the development of a quantitative Sustainability Indicator Framework that could be used to evaluate MWTTS specifically and also to drive the technology development process. This objective has been considered here and is reported below.

2.2 RESEARCH OBJECTIVES

The objectives of this study were to:

1. Investigate to what extent IBL indicators are considered during the selection of MWTTs within the South African mining sector and the degree of actual implementation of the IBL indicators in the assessment and selection of MWTTs in South Africa;
2. Investigate the perceived need in the mining sector in South Africa for a generic framework for the evaluation and selection of MWTTs and to establish how the selection criteria of MWTTs differs at the operational and post-closure phases of the mine;
3. Identify and compare key sustainability indicators that stakeholders in the mining industry both in a developing (e.g. South Africa) and developed country context consider important when choosing between MWTT options;
4. Formulate a set of suitable sustainability indicators with quantitative indicators that: (a) may guide the process of research and development of MWTTs in general and the scale-up development of the Rhodes BioSURE process in particular, and (b) may be used in the assessment and selection of MWTTs to improve the sustainability of AMD operations.

2.3 RESEARCH METHODS

Interviews and questionnaires were used as the basic research tools in this study, with mining industry personnel who are intimately involved with the technology selection process, as the subjects. Being a highly specialised industry sector, the number of potential subjects was not expected to be large. A total of 20 experts and professionals (scientists, chemical engineers, geohydrologists, technology developers, technology implementers, environmental managers, environmental consultants, water quality experts, social scientists, researchers and policy makers) were identified from a Water Institute of Southern Africa's (WISA) membership database as potential subjects in this study, out of which 16 responded to the request and were successfully interviewed and also completed the questionnaire. They were drawn from a range of local and multinational organisations in the mining and other ancillary industries involved in mine wastewater treatment in South Africa (**Table 2.1**). Oral interviews were conducted with all the subjects, after which they were asked to complete a structured questionnaire. The interviews were designed to identify the MWTTs selection criteria currently used in the industry and to capture the thinking and understanding of the subjects on relevant sustainability indicators. The subjects were first asked about the selection criteria without prompting and then were asked about specific issues if not already mentioned. The questionnaire was designed to capture the quantitative indicators of various sustainability indicators for possible integration in the development of a Sustainable Indicator Framework. The indicators used were identified from the literature (Larsen and Gujer, 1997; Lettinga, 2001; Hellström *et al.*, 2000; Hoffman *et al.*, 2000; Dunmade, 2002; Larsen and Lienert, 2003; Bracken, 2005).

Table 2.1 Profile of companies from which subjects were drawn.

Type of organisation sampled	No of organisations approached	No of organisations that responded
Gold mining companies	3	2
Petrochemical manufacturing companies	1	0
Coal mining companies	4	4
Mining/Environmental consultancies	5	5
Mining business interest organisations	1	1
Wastewater treatment companies	1	1
Research organisations	2	2
Funding organisations	1	1
Government department/ministries	2	0

Experts' views have been recognised as constituting the "push" variable in the change equation of the decision-making process in environmental progress as they are the key influencers on decision-makers in both the public and private sectors (Miller, 1997). Furthermore, according to Bardos *et al.* (2000), the views of different stakeholders are valuable in eliminating potential decision-making conflicts. This was considered feasible since the recording of choices as individual rankings may be combined to provide an overall ranking, and a degree of objectivity in the ranking process, when more than one expert or stakeholder is consulted. The full questionnaire, in which weights on a Likert scale of 1 to 5 (where 1 = least important, 5 = extremely important) were assigned to each indicator (**Appendix 1**). All interviews were tape-recorded in order to minimise the possibility of misinterpretation of information, and also to optimise the flow of dialogue. The questionnaire was designed to assess the weighting of various sustainability indicators at the operational and post-closure phases of mine operation in a developing and developed country context for incorporation during the development of the proposed framework (**Table 2.2**). The questionnaire was used to quantify, through a rating regime, the priority IBL indicators expounded during the interview, in addition to a much more comprehensive list of sustainability indicators within each of the five broader categories relevant to the evaluation and selection of MWTTs in the context of sustainable development. These were assessed for both the operational and post-closure phases of the mine in a developing and a developed country context. All of the 16 subjects worked in a developing country context (South Africa) while 50% had also worked or consulted at one time in a developed country context (United States of America, United Kingdom, Canada, and Australia). The latter completed the section of the questionnaire which was designed to rate the indicators as used in MWTT evaluation and selection in the developed country context.

Table 2.2 Organisation of the questionnaire designed to capture quantitative indicators for sustainability indictors in the development of the Sustainability Indicator Framework.

		Level of Assessment			
		Developing Countries		**Developed countries**	
Section	**Objective**	**Operational Phase**	**Post-closure phase**	**Operational Phase**	**Post-closure phase**
Section 1	Weighting of IBL indicators	x	x	x	x
Section 2	Weighting of comprehensive social indicators	x	x	x	x
Section 3	Weighting of comprehensive environmental indicators	x	x	x	x
Section 4	Weighting of comprehensive financial indicators	x	x	x	x
Section 5	Weighting of comprehensive technical indicators	x	x	x	x

The enthusiasm with which the questionnaire was completed in this study was indicative of the interest and importance that the various stakeholders ascribed to the development of a specific tool for the evaluation and assessment of MWTTs in the mining industry. It has been observed that stakeholder participation in the decision-making process strengthens the attainment of sustainable development objectives (UK Round Table on Sustainable Development, 1998).

2.3.1 The Analysis of Questionnaires

It was considered that the means or standard deviations could not adequately account for the wide degree of variation in the subjects' judgements of the importance of the indicators. For example, for a specific indicator where there was strong agreement as to the importance weighting, the standard deviation would be low, while for those indicators where there was a lack of agreement, the standard deviation would be higher than the differences between the allocated mean weights of the indicators. For this reason an importance index is calculated for each indicator by dividing the mean weight allocated to the indicator with its standard deviation. This calculated value was named the Actual Importance Index (AII) (Whittington-Jones, pers. com. 2006; Radloff, pers. com. 2006). An AII value of 4 and above was interpreted as constituting agreement on the high importance of an indicator from the mining industry's perspective, an AII value of between 2 and 3.9 as moderately important, while an AII value of 2 or less was of low importance or considered unimportant. Statistical analysis, including one-way analysis of variance (ANOVA) (Scheffé Post Hoc test) and repeated measures ANOVA, was performed using the software package Statistica (data analysis software system) Version 7.1 (StatSoft, Inc. 2005). This was done to verify whether the rating of the IBL indicators and the various indicators based on AII values were significantly different within and between the various phases for both the developing and developed country contexts. These were reported at the 95% level of confidence, where $p<0.05$ was significantly different and $p>0.05$ was not significantly different.

2.4 RESULTS AND DISCUSSION

A quantitative analysis of the results of the questionnaire, presented in the following sections, is undertaken for the development of the Sustainability Indicator Framework, leading to the development of a Conceptual Decision-Support System.

2.4.1 Interview Study

Table 2.3 summarises the results obtained in the interview process. A significant proportion of the subjects (93%) expressed the need for some form of tool or guideline specifically designed for the assessment, selection and development of technologies for mine wastewater treatment. Such guidelines were generally considered to be unavailable to the industry at time with all the subjects (n=16), indicating the absence of documented in-house guidelines for this purpose.

Table 2.3 A summary of responses of the interviews on mine water treatment technology selection criteria (n=16).

	Research question	**Yes (%)**	**No (%)**	**Agreement on Prompting (%)**
1	Need for generic technology assessment framework for AMD treatment	93	7	-
2	Presence of documented in-house guidelines for evaluation/selection of AMD treatment technologies	0	100	-
3	Awareness of existing frameworks/guidelines for AMD treatment technologies	19	81	100
4	Use of some form of arbitrary guidelines for evaluation and selection of AMD treatment technologies	100	0	
5	Main criteria used for evaluation and selection of AMD treatment technologies:			
	-Costs (capital costs, operation and management costs)	100	0	-
	-Technical applicability/feasibility/effectiveness)	100	0	-
	-Government approval and “proven status” of technology	100	0	-
	-Environmental impacts (water pollution and waste disposal)	44	56	100
	-Social impacts(health and safety, reuse of treated water)	31	69	100
6	Separate development of evaluation/selection criteria for operational and post-closure phases of mine	81	19	-
7	Role of external mining community’s opinion in technology selection/evaluation	100	0	-

However, a small percentage of subjects (7%) believed there was no need for the development of a generic technology assessment instrument, citing site specificity, different AMD water chemistry, different target treatment objectives (discharge standards), the prevailing conditions of receiving water bodies and the different classes of the receiving catchments (e.g.

pristine condition or varying degrees of pollution) as reasons. Only 19% of the subjects were aware of the existence of some form of structured framework for guidance in technology evaluation and selection in the mining industry, while a significant proportion (81%) had no knowledge of the existence of any specific framework for such an exercise.

The guidelines mentioned include technical or decision guides for selecting technologies for mine wastewater treatment technologies published by Pulles *et al.* (1996), a conceptual decision model for the design of passive treatment systems (Hedin, 1997), and a report produced by Golder Associates South Africa for Coaltech 2020 entitled "Evaluation of New and Emerging Mine Water Treatment Technology" which is not available in the public domain.

None of the subjects had made use of, or was aware of the existence of structured and comprehensive generic technology assessment frameworks such as the EnTA and the CTSA. It was interesting to note that expression of the need for such a framework by the subjects (93%) agreed with the observed lack or absence (100%) of any such formal or structured in-house instrument. All subjects make use of some form of basic criteria of their own when evaluating and selecting technologies for mine wastewater treatment. These were mainly based on techno-economic grounds. The main criteria used by the subjects were found to be costs (100%), technical/technological applicability (100%) and government approval and "proven status" of technology (100%). Environmental criteria were used by 44% (**Table 2.3**) and considerations included impacts on surface and ground water, and waste generation and disposal. It should be noted, however, that the waste generation and disposal consideration appeared to be largely motivated by cost implications rather than by the actual environmental consequences of waste generation and disposal. The 56% of the subjects who made no mention of the use of environmental impacts when evaluating and selecting technologies did, however, concede that the environment was an important consideration when specifically asked about the importance of the environmental impacts of technologies in technology evaluation and selection. Social impacts were not viewed as critically important in the evaluation and selection process as only 31% of the subjects reported that they sometimes included social criteria (mainly health and safety, and potential reuse of the treated water) in technology evaluation and selection. However, 100% of the subjects, who did not mention the use of social impacts initially, also conceded that social impacts were important in the evaluation and selection of MWTTs, although a small percentage (13%) maintained that social impacts were hardly a consideration in practice.

While 81% of the subjects indicated that a separate set of criteria should be developed for evaluation and selection of technologies for the operational and post-closure phases of the mine, 19% believed that the evaluation and selection criteria should done in view of the eventual operation of the technology at mine closure. Of those subjects who supported separate criteria for the two phases, none could provide suggestions as to the key differences between selection criteria. Although no consistent set of criteria emerged for the two phases, the consensus was that the criteria developed for the operational phase should be based around active treatment objectives while the criteria for the post-closure phase should be based around passive treatment objectives. Some of the criteria proposed for consideration at the post-closure phase included the potential to generate revenue, minimal operational requirements, affordability, simple technology inputs and the employment of local people. Although 100% of the subjects agreed that the opinion of the local communities external to the mines should count in the evaluation and selection of MWTTs, they conceded that more often than not, technological choices are too complex for such communities to comprehend and, as such, no meaningful inputs could actually be made by such communities. However, they were, as required by law, consulted during the public participation process dictated by EIA and Environmental Management Program Reports (EMPR) requirements in South Africa (DEAT, 2004; Bosman and Cotzé, 2005).

The above results showed that while most of the subjects and their organisations, especially the multinational companies, placed a high premium on sustainability issues at the organisational policy level, these were not being comprehensively applied in the evaluation and selection of technologies designed to treat mine wastewater. The results showed that technology evaluation and selection is premised primarily on technical and financial considerations, with environmental and social considerations playing rather minor roles, which is at odds with corporate commitments to sustainable development. This suggested that in most mining companies the IBL theme was not spread across all the business activities, or at least not in the selection and adoption of MWTTs.

A possible explanation for this observation could be that mine waste water treatment is not viewed as a core business function within the mining industry. Nevertheless, considering the large capital commitments set aside for this responsibility, and the potential liabilities that mining companies face should they be found non-compliant in this regard, it is critical that their commitment, not just towards mine water treatment, but also towards the overall sustainability of the technologies they adopt to treat mine water, be re-evaluated.

In order to validate the above observations and to develop relative quantitative indicators for the various sustainability indicators, a more detailed analysis of the questionnaire was undertaken and the results are presented below. The relative importance of the IBL indicators and detailed sustainability indicators under each IBL indicator at the operational and post-closure phases of mine operation was examined in a developing and a developed country context.

2.4.2 Questionnaire Analysis

2.4.2.1 The Importance of Integrated Bottom Line Indicators in Mine Water Treatment Technology Assessment.

Developing Country Context

The subjects' judgment as to the relative importance of the IBL indicators during the operational and post-closure phases of a mine in a developing context is presented in **Figure 2.1**. Although most of the IBL indicators received high mean weights (3.5-4.5), there was little agreement on the actual importance of most of the indicators during either the operational or post-closure phases as indicated by the relatively high standard deviations (**Figure 2.1**). This then translated into a lower AII value. Environmental, economic and technical indicators were rated as being highly important during both phases (AII value >4), with economic indicators being the most highly rated (AII=7.3) and legal indicators being the least rated (AII=3.6) during the operational phase. During the post-closure phase, however, only economic indicators were judged as being highly important (AII=6.3), with legal indicators again receiving the lowest rating (AII=3.2). There were significant differences in the AII rating of the IBL indicators within the operational phase (ANOVA, df= 4, $p<0.05$) and within the post-closure phase (ANOVA, df= 4, $p<0.05$). Economic indicators were rated significantly higher than all the other IBL indicators (ANOVA, $p<0.05$) during the operational phase and also during the post-closure phase (ANOVA, $p<0.05$).

In a developing country context, no significant difference in the weighting of the indicators was observed when the operational and post-closure phases were compared based on the AII scores (ANOVA, df=4, p>0.05). However, economic indicators were considered the most important indicators, and were rated higher during the operational phase (AII=7.3) than during the post-closure phase (AII=6.3). This was followed by environmental (AII=4.5) and technical indicators (AII=4.1), respectively, during the operational phase. Environmental (AII=4.5) and legal (AII=3.9) indicators were rated higher during the operational phase than during the post-closure phase, although legal indicators were considered moderately important (2<AII<3.9) during the post-closure phase. Social indicators were, considered moderately important (2<AII<3.9) and were rated equally during both phases.

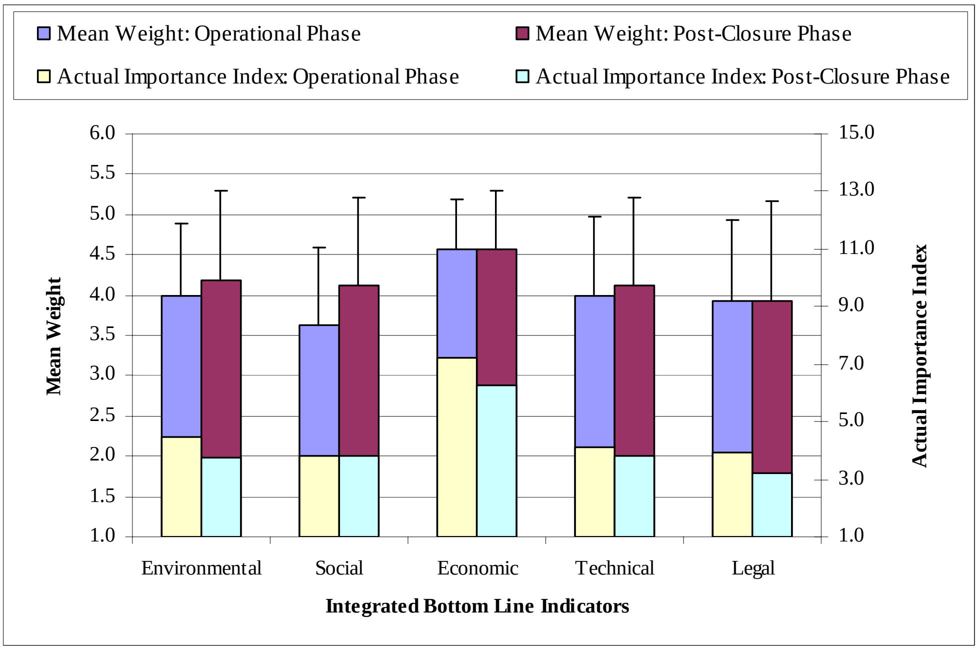

Figure 2.1 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to integrated bottom line (IBL) indicators for mine water treatment technology (MWTT) development and selection in a developing country context by 16 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

The results confirmed the observation from the interview study that economic sustainability constituted the major pillar on which MWTTs selection was based, with the other IBL indicators not receiving the attention they possibly deserve. While there may be commitment to environmental management during the operational phase, this does not appear to be reflected in the selection of MWTTs. This may also have been a consequence of the compulsory funds set aside for rehabilitation purposes after mine closure as stipulated by the MPRD Act of 2002 which, in essence, may be perceived to take away some degree of responsibility for these issues by the mines. In broad terms, these results revealed a fundamental weakness in the MWTTs evaluation and selection system used in the industry in which broader sustainability issues are overlooked, especially at a time when sustainability has been identified as one of the key challenges facing the mining sector(Azapagic, 2004).

Developed Country Context

Figure 2.2 shows the subjects' judgement as to the relative importance of IBL indicators during the operational and post-closure phases in a developed country context. Except for social indicators, the indicators scored greater than 2 on the AII and were therefore judged as being moderately or highly important during both phases. There were significant differences in the AII of the indicators within the operational phase (ANOVA, df=4, p<0.05) and within the post-closure phase (ANOVA, df=4, p<0.05). Within the operational phase, legal indicators were the most highly rated (AII =13.8) and were rated significantly higher than all the other indicators (ANOVA, p<0.05) while social indicators were the least rated (**Figure 2.2**). It should be noted that the very high AII value obtained for legal indicators resulted from a very low standard deviation i.e. strong agreement amongst subjects. Within the post-closure phase, technical indicators were the most highly rated (AII=8.3) and were rated significantly higher than all the other IBL indicators (ANOVA, p<0.05).

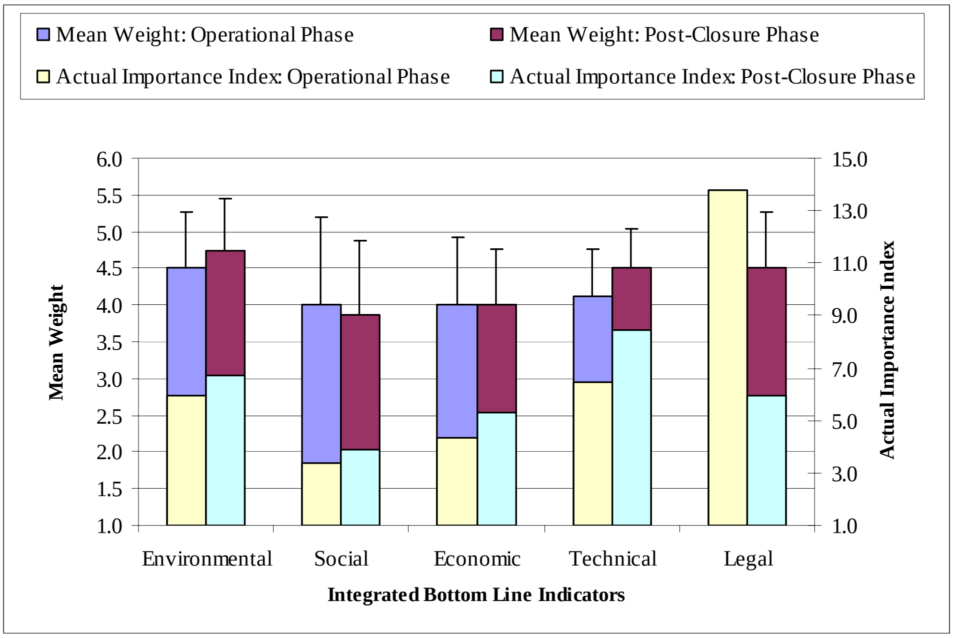

Figure 2.2 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to integrated bottom line (IBL) indicators for mine water treatment technology (MWTT) development and selection in a developed country context by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

The IBL indicators were rated significantly differently when the operational and post-closure phases were compared based on the AII scores (ANOVA, df= 4, p<0.05). Legal, technical, economic and environmental indicators were rated highly, with technical, environmental and economic indicators rated significantly higher during the post-closure phase than during the operational phase (ANOVA, p<0.05). Legal indicators were rated significantly higher during the operational phase than during the post-closure phase (ANOVA, p<0.05). The importance of legal indicators declined by as much as 51% during the post-closure phase, while that of technical indicators increased by a similar margin (50%) during the same phase. This may suggest a perception of relaxed enforcement of legislation during the post-closure, resulting in a trade-off of legal concerns with a sustainable technological environment. It was perhaps not surprising that economic indicators did not receive the highest score as was observed for the developing country context. The fact that economic indicators were judged less important during the operational phase than legal, technical and environmental indicators during both phases could be attributed to the fact that developed countries are generally more affluent than their developing counterparts and would be expected to afford the treatment technologies chosen. That the highest ratings were given to legal indicators (AII=13.8), in addition to high ratings for environmental (AII=5.9) and technical indicators (AII=6.4), may be attributed probably to a higher level of environmental awareness and of a higher level of law enforcement in a developed country than in developing countries. The low rating of social indicators during both phases may be attributed to the higher level of overall development expected in a developed country context.

A comparison of the ratings of the IBL indicators during the operational phases between developing and developed country contexts (**Figure 2.3**) showed the indicators were rated significantly differently (ANOVA, df= 4, p<0.05).

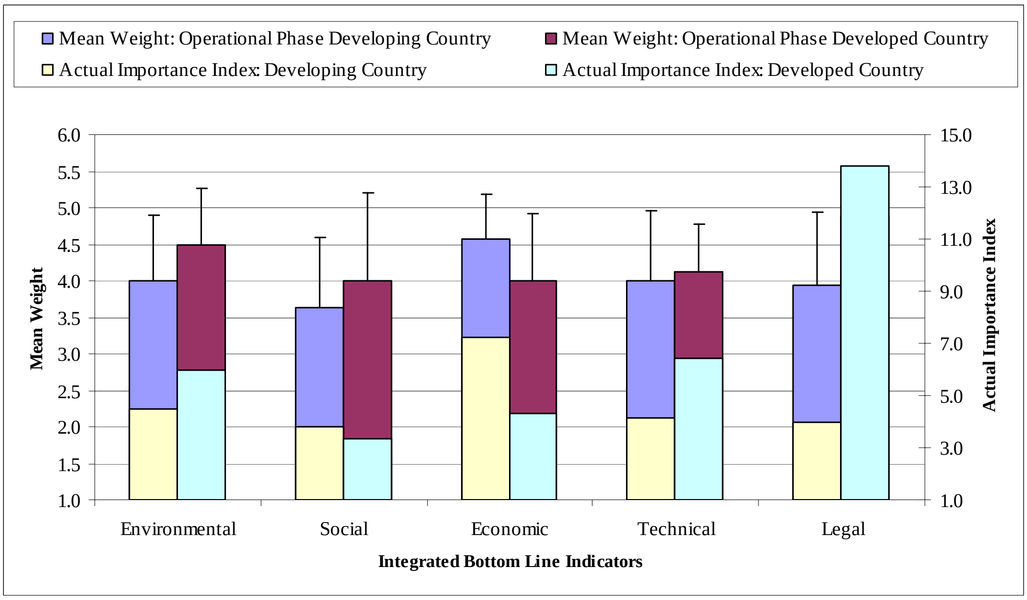

Figure 2.3 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to integrated bottom line (IBL) indicators for mine water treatment technology (MWTT) development and selection during the operational phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= mean Weight Divided by Standard Deviation.

Environmental, legal and technical indicators were rated significantly higher during the operational phase in a developed country context than during the same phase in a developing country context (ANOVA, p<0.05). However, economic indicators were rated significantly higher during the operational phase in a developing country context (ANOVA, p<0.05) than in a developed country while social indicators were not rated significantly differently during the two phases in both developing and developed countries (ANOVA, p>0.05).

A comparison of the rating of the IBL indicators during the post-closure phases in both developing and developed country contexts (**Figure 2.4**) showed a similar trend as observed during the operational phase, with the indicators rated significantly higher at the post-closure phase in a developed country context (ANOVA, df= 4, p<0.05). Environmental, technical, and legal indicators were rated significantly higher during the post-closure phase in a developed country context than in a developing country context (ANOVA, p<0.05) while social indicators were rated comparably during both phases in both the developing and developed country contexts (ANOVA, p>0.05). It was expected that technical indicators would be considered more important during the post-closure in a developing country context than a developed country context but this was not the case. Developed countries are generally perceived to be more technologically advanced and as such one would expect the availability of expertise, skills and spare parts in these countries that would make the difference.

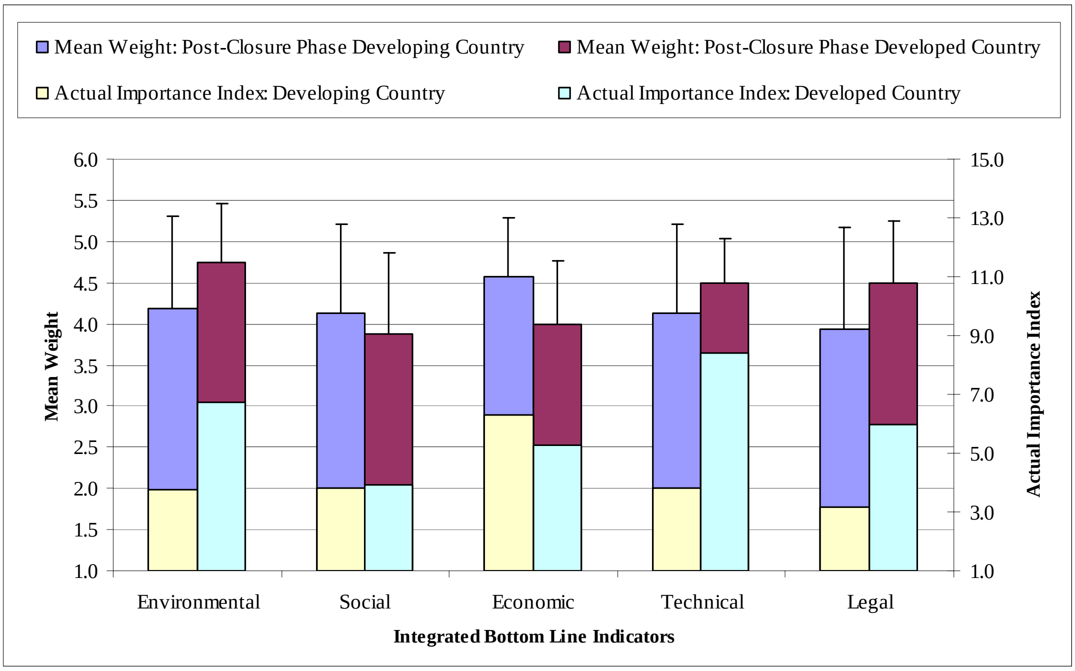

Figure 2.4 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to integrated bottom line (IBL) indicators for mine water treatment technology (MWTT) development and selection during the post-closure phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= mean Weight Divided by Standard Deviation.

The IBL indicators of environmental, social, economic and technical factors were comprised of a detailed range of sustainability indicators put to the subjects (**Table 2.4**). These were compiled from literature (Larsen and Gujer, 1997; Lettinga, 2001; Hellström *et al.*, 2000; Hoffman *et al.*, 2000; Dunmade, 2002; Larsen and Lienert, 2003; Bracken, 2005) and the analysis of each is dealt with separately below

Table 2.4 Detailed list of the integrated bottom line sustainability indicators used in this study.

Environmental Indicators	**Social Indicator**	**Economic Indicators**	**Technical Indicators**
Abiotic depletion	Health and safety	Wastes disposal cost	Flexibility and adaptability
Natural resource depletion potential	Reuse of treated water	Capital costs	Efficiency of process
Land area requirement	Indirect employment	Operational & management cost	Effectiveness of treatment
Ecotoxicity potential	Direct employment	Cost of spares	Ease of operation
Phytotoxicity potential	Education and training	Decommissioning fees	Process reliability
Energy depletion potential	Maintenance of cultural heritage	Licence fees	Ease of maintenance/replacement of part
Global warming potential	Maintenance of social structures		Robustness of technology/process
Acidification potential	Social perception		Durability of plant & spares
Nitrification potential	Political stability		Susceptibility to mechanical failure
Eutrophication potential	Institutional Support		Local availability of system experts
Bioaccumulation potential			Availability of spares
Ozone layer depletion potential			Onsite/local solution
Photochemical oxidant creation			Ease of construction
Reuse of raw materials potential			Level of automation
Generation of useful by-products			Reliance on labour
Quantity of wastes			
Toxicity of wastes			
Effect on biodiversity			
Potential to attract Pests/Vermin			
Toxicity of raw materials			
Aesthetics			
Odour generation			
Availability of special waste disposal sites			

2.4.2.2 Environmental Indicators

A number of interesting observations can be made from **Figure 2.5** which represents the subjects' judgements on the relative importance of a range of environmental indicators for consideration in MWTTs evaluation in a developing country context. While the mean weights assigned to most of the indicators were relatively high, there was very little agreement among the subjects as to the importance of the indicators. This resulted in very low AII values for almost all of the indicators. Of particular note was the high mean weight of 4.43 for acidification potential during the operational phase which, when transformed, yielded a very low AII value of 1.7. Almost all the indicators were judged as being moderately important (2<AII<3.9) during both phases, with only 9% and 17% of the 23 indicators being judged as highly important (AII>4) during the operational and post-closure phases, respectively. During the operational phase, toxicity of wastes (AII=5.5) and the quantity of wastes generated (AII=4.3) were the most highly rated. Ozone layer depletion (AII=1.9), effect on biodiversity

(AII=2.2) and potential to attract pests and vermin (AII=2.1) were the lowest rated indicators in importance during the operational phase.

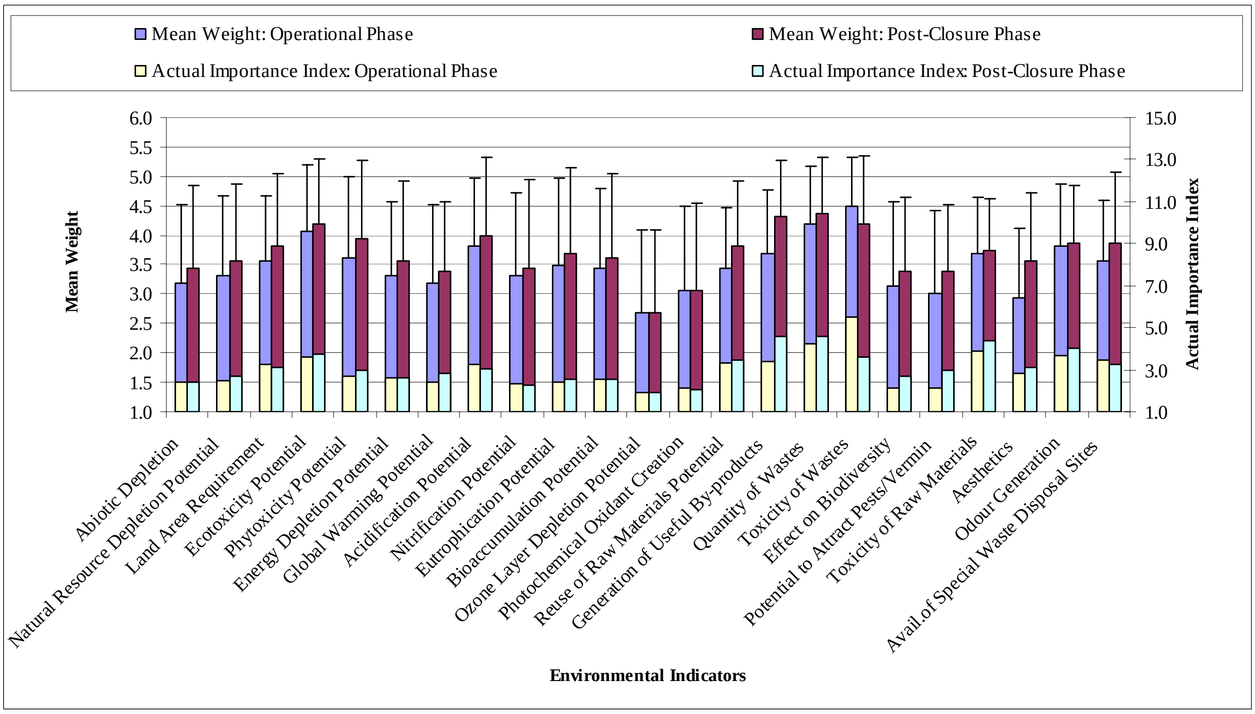

Figure 2.5 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to environmental indicators for mine water treatment technology (MWTT) development and selection in a developing country context by 16 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

During the post-closure phase, the generation of useful by-products (AII=4.6), toxicity of raw materials (AII=4.4), quantity of wastes (AII=4.6) and odour generation (AII=4.1) were the most highly rated while ozone layer depletion (AII=2.2) and nitrification potential (AII=2.3) received the lowest AII scores. It was also observed that the indicators were rated significantly differently within the operational phase (ANOVA, df= 22, $p<0.05$) and within the post-closure phase (ANOVA, df= 22, $p<0.05$). Within the operational phase, toxicity of wastes was rated significantly higher than all other indicators (ANOVA, $p<0.05$).

The data also revealed a slight shift in emphasis of the relative importance of the majority of the indicators as the mine moved from the operational to the post-closure phase in a developing country context. Of these indicators, 13% were rated significantly higher during the post-closure phase than during the operational phase (ANOVA, $p<0.05$) while only toxicity of wastes (4%) was rated significantly higher during the operational phase than during the post-closure phase (ANOVA, $p<0.05$). The indicators weighted significantly higher during the post-closure phase included the effect on biodiversity, generation of useful by-products, and attraction of pests and vermin. The attraction of pests and vermin is closely linked to primary health care delivery in developing countries where malaria and other communicable diseases may be a serious problem. It was surprising therefore that this indicator was rated as being unimportant during the operational phase as the mine treatment function may present potential breeding grounds for vectors of various diseases, with serious health and thus productivity implications for staff and surrounding communities.

Biodiversity, emissions, energy use, nuisance, global warming and other environmental impacts, land use, management and rehabilitation, and product toxicity were identified as some of the key sustainability issues for the mining and mineral industry (Azapagic, 2004). Seghezzo (2004) further recommended that in assessing technologies, consideration should be paid, where feasible, to long-term aspects on regional, continental and global scales. As such, it was surprising to observe that topical regional and global environmental concerns such as biodiversity, global warming, and ozone layer depletion potential were considered unimportant (AII < 2) by all of the subjects in the evaluation of MWTTs during both phases of mine operation (**Figure 2.5**). It was observed that with the exception of quantity of wastes, toxicity of wastes, ecotoxicity potential and the availability of special waste disposal sites, all other localised environmental concerns such as natural resource depletion, phytotoxicity potential, acidification potential, eutrophication potential, bioaccumulation potential and toxicity of raw materials were all judged as being moderately important. This observation broadly agreed with the observation by Palme *et al.* (2005) that linking the various long-term and global aspects of sustainable development to the decision-making process, is one of the major difficulties companies face when developing sustainable development indicators.

It was also surprising to note that the subjects did not consider indicators such as energy depletion potential and the reuse of raw materials important. It was expected that these indicators would have been overwhelmingly judged as being important in the evaluation of MWTTs, especially since economic considerations emerged as the main criterion. The use of energy and the reusability of raw materials all have potential financial savings implications and are also important aspects of the industrial ecological approach to environmental management. It is expected that with the ever increasing cost of energy, technologies that make use of little (energy efficient technologies) or no energy would be preferred over technologies which have high energy requirements. Furthermore, the use of energy is correlated with the depletion of non-renewable resources such as fossil fuels and the atmospheric emission of green house gases such as carbon dioxide, nitrogen oxides and sulphur oxides (Azapagic, 2004). As such, energy efficient technologies would therefore be expected to lead to reduced depletion of fossil resources and reduced atmospheric emissions (Azapagic, 2004).

Developed Country Context

In a developed country context subjects placed greater premium on both the global and localised environmental indicators during both the operational and post-closure phases than for developing countries. This was reflected in higher mean weights and AII values (**Figure 2.6**). However it should be noted that only 48% and 57% of the indicators were considered highly important during the operational and post-closure phases respectively. The generation of useful by-products (AII=11.7), toxicity of raw materials (AII=9.2), abiotic depletion (AII=8.1), quantity of wastes (AII=8.9) and toxicity of wastes (AII=8.4) were rated higher than other indicators within the post-closure phase, while ozone layer depletion (AII=1.9), effect on biodiversity (AII=2.5) and nitrification potential (AII=2.5) received the lowest rating at the post-closure phase The indicators were rated significantly differently within the operational phase (ANOVA, df= 22, $p<0.05$) and also within the post-closure phase (ANOVA, df= 22, $p<0.05$).

The indicators were rated significantly differently when the operational and post-closure phases were compared based on AII scores (ANOVA, df=22, $p<0.05$). 26% of the indicators were rated significantly higher during the post-closure phase than during the operational phase. These included land area requirements (AII=6.9), the generation of useful by-products (AII=11.7), quantity of wastes (AII=8.9) and toxicity of raw materials (AII=9.2). The increase in importance of the rating of land area requirements and the generation of useful by-products during the post-closure phase also suggested the need for some contribution to economic sustainability during this phase. Only bioaccumulation potential (4%) was rated significantly higher during the operational phase than during the post-closure phase in a developed country context (ANOVA, p<0.02).

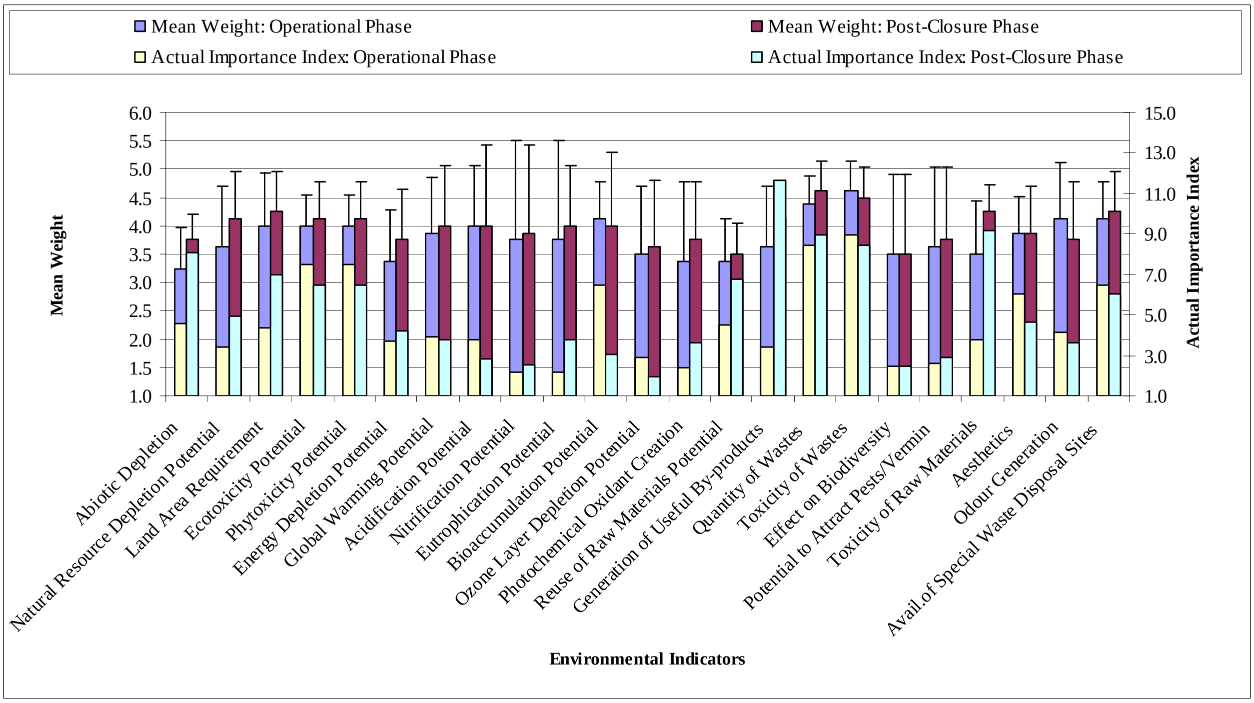

Figure 2.6 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to environmental indicators for mine water treatment technology (MWTT) development and selection in a developed country context by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

That indicators such as energy depletion potential, global warming and ozone layer depletion potential were among the indicators judged as moderately important was rather surprising as developed countries are generally perceived to be more environmentally aware and responsible, with most having endorsed international environmental protocols such as the Kyoto Protocol (United Nations, 1998). Furthermore, the judgement by the subjects on the reuse of raw materials potential and the generation of useful by-products as unimportant during the operational phase was also unexpected as these indicators have industrial ecology undertones. Developed countries generally have limited land and the principles of industrial ecology may help ease the burden of pollution in these regions. The data further showed that the importance of the generation of useful by-products increased by more than 100% from the operational to the post-closure phase (**Figure 2.6**), suggesting a strong need for some form of economic interest or social investment after mine closure. In contrast this was not observed in the developing country context, where one would have expected a higher degree of interest in economic sustainability after mine closure, given that the economic resources in these regions are generally stretched (**Figure 2.5**).

A comparison of the rating of the indicators during the operational phase between a developing and a developed country context revealed that the indicators were rated significantly differently during the two contexts (ANOVA, df= 22, p<0.05). 61% of the indicators were rated significantly higher in a developed country context (ANOVA, p<0.05) than in a developing country context (**Figure 2.7**). These included ecotoxicity potential, phytotoxicity potential, quantity of wastes, toxicity of wastes, aesthetics and the availability of special waste disposal sites. The indicators were also rated significantly differently when the post-closure phases between a developing and developed country context were compared (ANOVA, df= 22, p<0.05). A comparative number of indicators (65%) was also rated significantly higher during the post-closure phase in a developed country context than in a developing country context (ANOVA, p<0.05) (**Figure 2.8**).

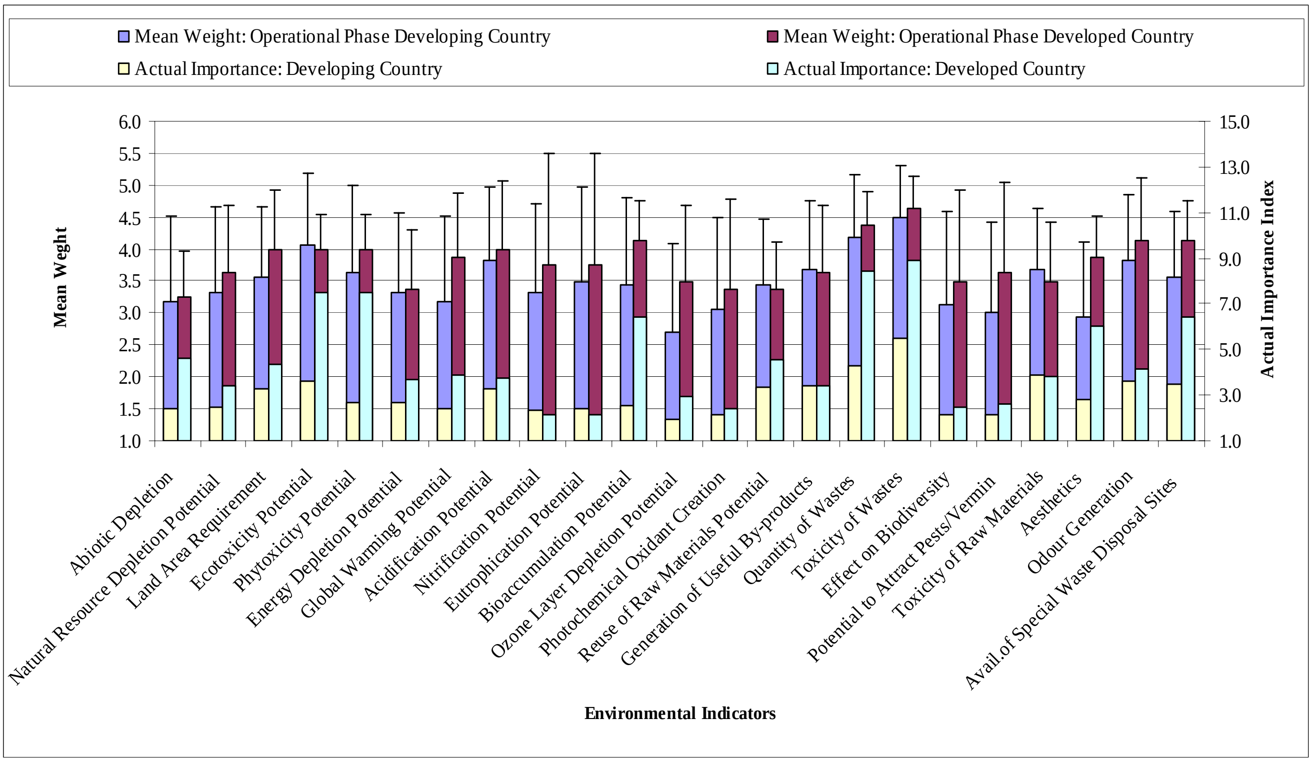

Figure 2.7 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to environmental indicators for mine water treatment technology (MWTT) development and selection during the operational phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= mean Weight Divided by Standard Deviation.

These included abiotic resources depletion potential, the generation of useful by-products, the reuse of raw material, quantity of wastes and toxicity of raw materials. Acidification potential, ozone layer depletion, effect on biodiversity and potential to attract pests and vermin were considered moderately important at both the developing and developed country contexts and were not rated significantly differently between both contexts (ANOVA, p>0.05).

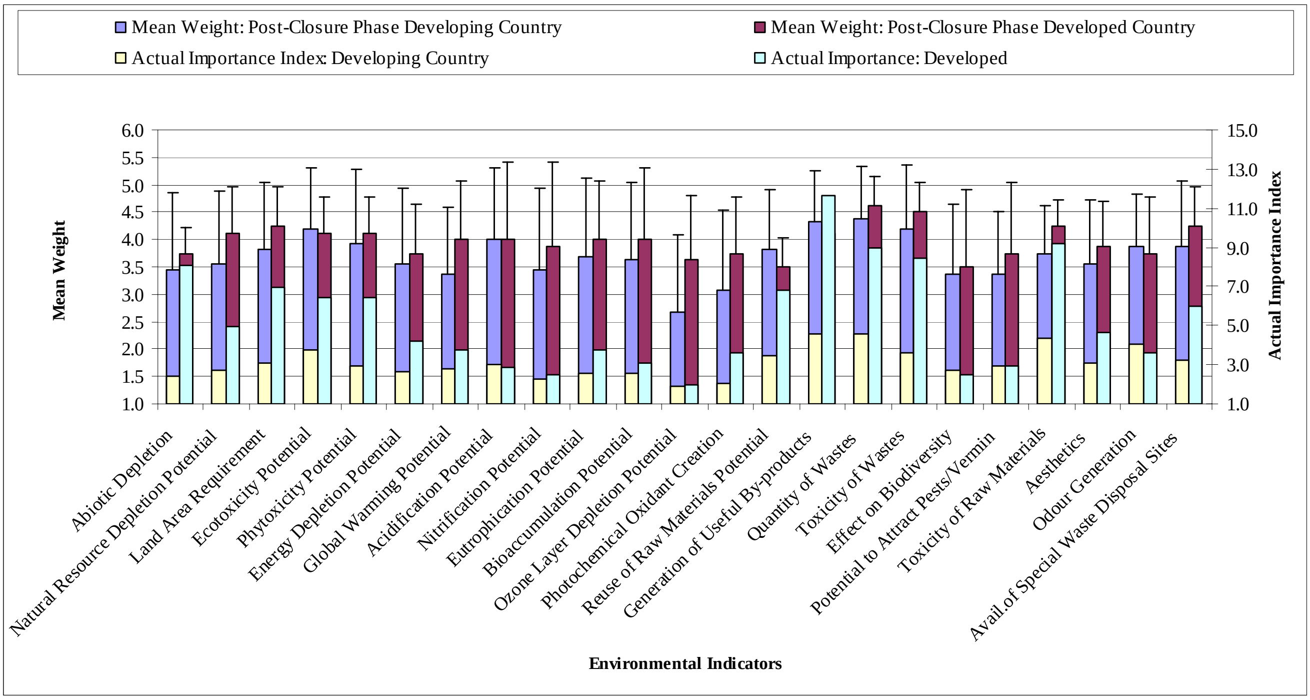

Figure 2.8 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to environmental indicators for mine water treatment technology (MWTT) development and selection during the post-closure phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= mean Weight Divided by Standard Deviation.

In broad terms, environmental indicators appeared to be more important in the assessment and development of MWTTs in a developed country context than in a developing country context, both during the operational and post-closure phases of mine operation.

2.4.2.3 Social Indicators

Developing Country Context

From a developing country's perspective, socio-cultural considerations may be very challenging, especially given that illiteracy and unemployment rates are usually high (Greany, 1996; EMM, 2003). Sound selection of mine water treatment technologies using formal sustainability criteria could play some role in the amelioration aspects of these social challenges. The subjects' judgements on the importance of social indicators for the evaluation and selection of MWTTs are presented in **Figure 2.9** for the operational and post-closure phases in a developing country context.

It can be observed that of the 10 social indicators surveyed, the subjects agreed that only 20% of these indicators were important for consideration during both the operational and post-closure phases. Health and safety considerations and the reuse of the treated water were the only indicators considered important during both the operational and post-closure phases with AII values of 4.5 and 5.5 respectively during the operational phase, and 5.2 and 4 respectively during the post-closure phase. The maintenance of cultural heritage (AII=2) and social structures (AII=2.3) received the lowest ratings during the post-closure phase.

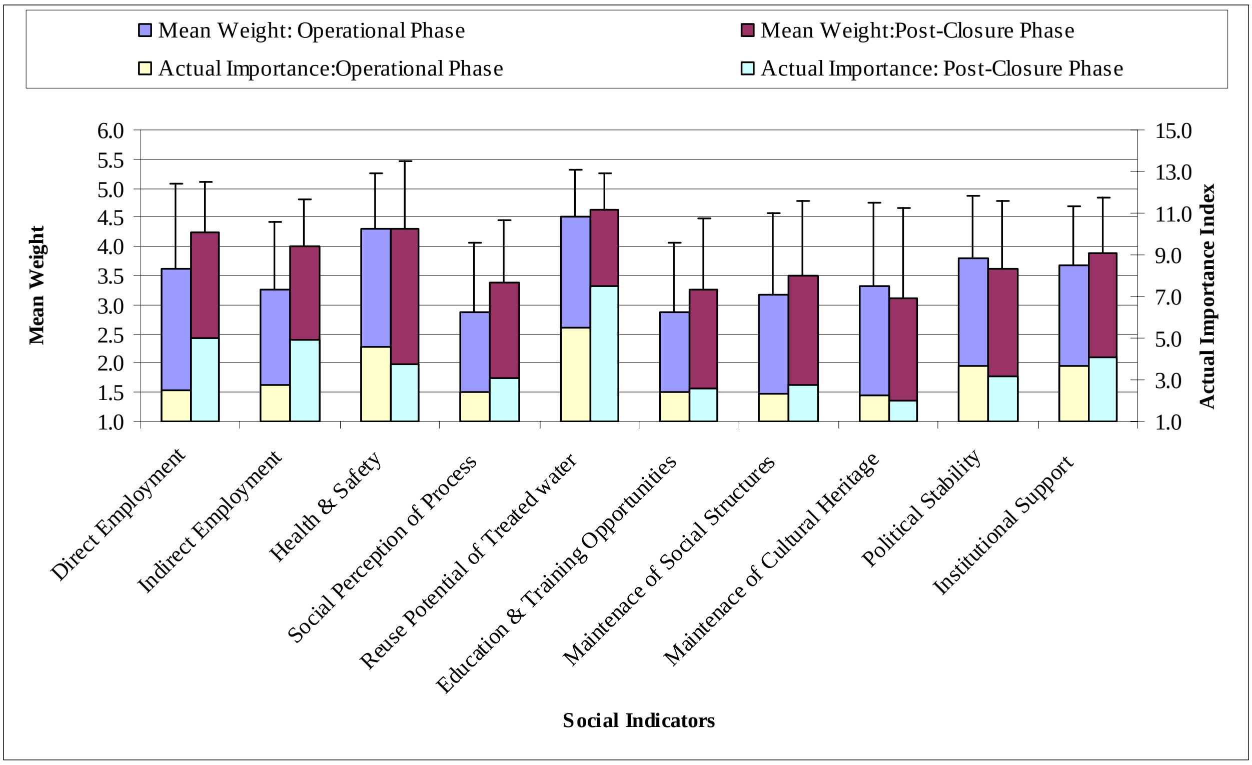

Figure 2.9 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to social indicators for mine water treatment technology (MWTT) development and selection in a developing country context by 16 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

That the subjects rated direct and indirect employment as being only moderately important during the operational phase in a developing country context was unexpected, as unemployment in these countries is generally a serious problem. There was, however, a significant difference in the rating of the importance of indirect employment when comparing the operational and post-closure phases (ANOVA, $p<0.05$), with this indicator considered more important during the post-closure phase than during the operational phase. It was surprising to observe that indicators such as direct and indirect employment were considered unimportant during the operational phase. This was unexpected as unemployment is generally viewed as one of the most serious constraints to sustainable development in a developing country context. This correlated with the earlier finding that economic indicators were the most important considerations and therefore appeared to suggest that passive treatment systems which attract less costs, including labour costs, may be the preferred treatment regime for AMD. The high AII value attributed to the reuse of treated water (AII=7.5) during post-closure, however, suggested the need for the sustaining of some form of economic interest or corporate social investment during this phase.

The rating of the indicators was significantly different during the operational phase (ANOVA, df= 9, $p<0.05$) and during the post-closure phase (ANOVA, df= 9, $p<0.05$). During the operational phase, health and safety (AII=4.6) and the reuse of treated water (AII=5.5) were rated significantly higher than the other indicators (ANOVA, $p<0.05$). The maintenance of social structures (AII=2.3) and maintenance of cultural heritage (AII=2.3) received the lowest ratings. On the other hand, the reuse of treated water (AII=7.5), direct employment (AII=4.9) and indirect employment (AII=4.9) were rated higher than the other indicators during the post-closure phase. Although both the reuse of treated water and indirect employment were rated as important during the post-closure phase, it was observed that the reuse of treated water was, however, rated higher than indirect employment. It should be noted that the high rating of the reuse of treated water contrasted with the low rating of indirect employment within the post-closure phase. One would have expected the rating of these two indicators to correlate since some degree of indirect employment opportunities is implicit in the reuse of the treated water. This suggested the inability of the role players to integrate the various sustainability issues in a holistic context when evaluating and selecting MWTTs. Politics and institutional support were not rated as highly important during either phase (**Figure 2.9**), which contradicted previous findings during the interview study that "government support" was one of the main criteria used by the industry to select between alternative MWTTs. These two indicators may arguably be very critical indicators in the sustainability of the mine water treatment function, as support from research institutions through continual research and development, for example, may lead to improvements in the technologies in the long term. Institutions and politics were found to be the most important social indicators in the sustainability of waste water treatment technologies in a study by Seghezzo (2004).

The rating of the indicators was significantly different between the operational and the post-closure phases (ANOVA, df= 9, $p<0.05$), with 30% of the indicators rated significantly higher during the post-closure phase than the operational phase. These included direct employment, indirect employment and the reuse of the treated water (ANOVA, $p<0.05$). The judgement that education and training opportunities were only moderately important during both phases (**Figure 2.9**) was not expected as this could be easily linked to the reuse of treated water, which was rated highly. Wad and Radnor (1984) emphasised the need to integrate local cultural aspects in the assessment of technologies, especially in developing countries. These indicators are at the very heart of sustainable development in the South African and, typically, in a developing country context. South Africa, and most developing countries, has a high unemployment and illiteracy rate (Greany, 1996; EMM, 2003), especially among the majority black population group. Given this socio-cultural background, it may be construed that for sustainable development goals to be realised, each and every opportunity that could be used to make a contribution should be seized. In the mining industry, the lack of locally available skills is frequently cited as a reason for outsourcing (Azapagic, 2004). Education and training and other skills development initiatives could contribute towards sustainable communities, especially after mine closure (Azapagic, 2004). The mine water treatment function, which is expected to continue long after mine closure, offers an excellent opportunity through which such sustainable communities could be further developed.

Developed Country Context

The results obtained for the weighting of social indicators for the operational and post-closure phases in a developed country context are illustrated in **Figure 2.10**. Of the 10 social indicators, only health and safety considerations (10% of the indicators) was judged by the subjects to be highly important both during the operational phase (AII=8.94) and post-closure phase (AII=10.26). There was a strong agreement as to the moderate importance of all the other indicators as they generally received comparatively low AII values ranging from 2.1 to 3.6 during the operational phase and from 2.0 to 3.8 during the post-closure phase.

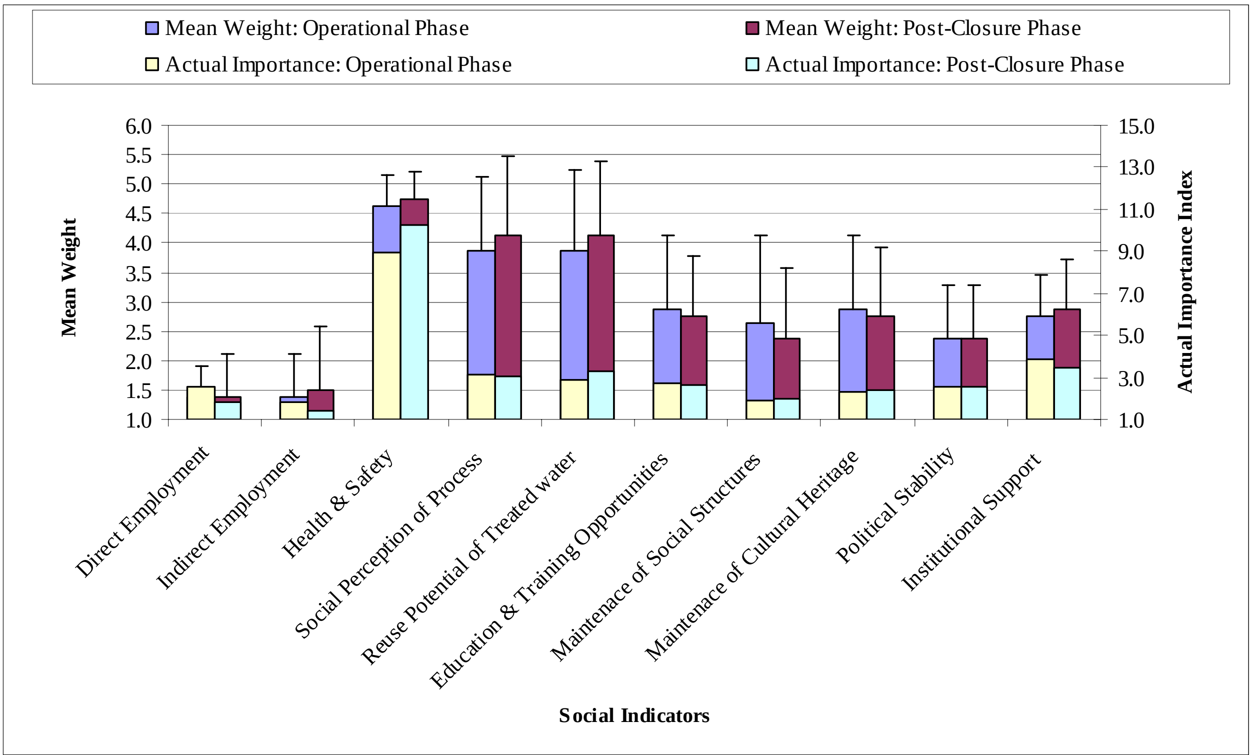

Figure 2.10 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to social indicators for mine water treatment technology (MWTT) development and selection in a developed country context by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

The indicators were rated significantly differently within both the operational phase (ANOVA, df=9, $p<0.05$) and the post-closure phase (ANOVA, df=9, $p<0.05$). During both the operational and post-closure phases, health and safety received the highest rating while indirect employment (AII=1.9) received the lowest.

The indicators were also rated significantly differently when the operational and post-closure phases were compared (ANOVA, df= 9, $p<0.05$). Health and safety considerations were rated significantly higher during the post-closure phase than during the operational phase (ANOVA, $p<0.05$). Although the reuse of treated water and political stability were judged as moderately important during both phases (2 >AII <4), they were, however, rated significantly higher during the post-closure phase than during the operational phase. Institutional support, which was also considered moderately important during both phases, was rated significantly higher during the operational phase than during the post-closure phase (ANOVA, $p<0.05$).

There was a significant difference in the rating of the indicators when the operational phases in both the developing and developed country contexts were compared (ANOVA, df= 9, $p<0.05$). It was observed that health and safety considerations were rated significantly higher during the operational phase in a developed country context than in a developing country context (ANOVA, $p<0.05$) while the reuse of treated water and political stability were rated significantly higher during the operational phase in a developing than a developed country context (ANOVA, $p<0.05$) (**Figure 2.11**).

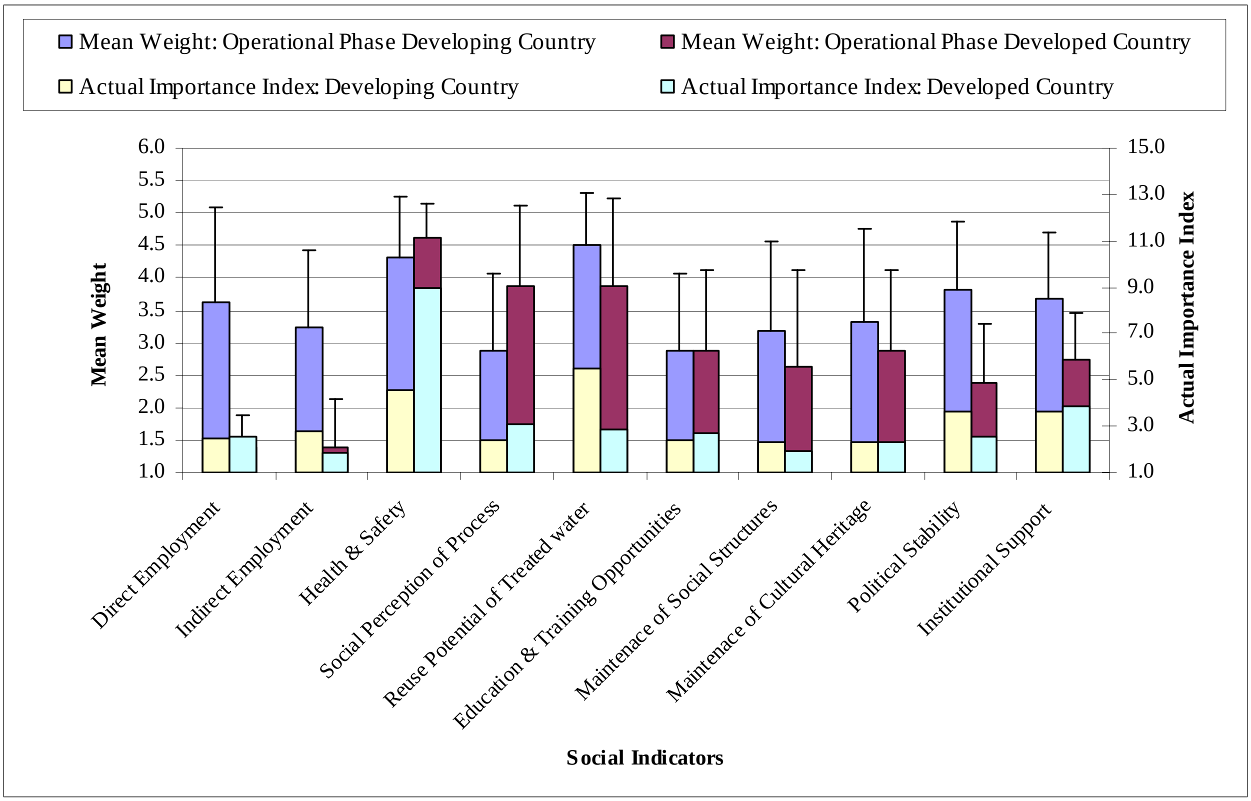

Figure 2.11 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to social indicators for mine water treatment technology (MWTT) development and selection during the operational phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= mean Weight Divided by Standard Deviation.

There was also a significant difference in the rating of the indicators during the post-closure phase between the developing and developed country contexts (ANOVA, df= 9, $p<0.05$). Direct employment, indirect employment and the reuse of treated water were rated significantly higher during the post-closure phase in a developing country context (ANOVA, $p<0.05$) while only health and safety considerations was rated significantly higher during the post-closure phase in a developed than developing country context (ANOVA, $p<0.05$) (**Figure 2.12**).

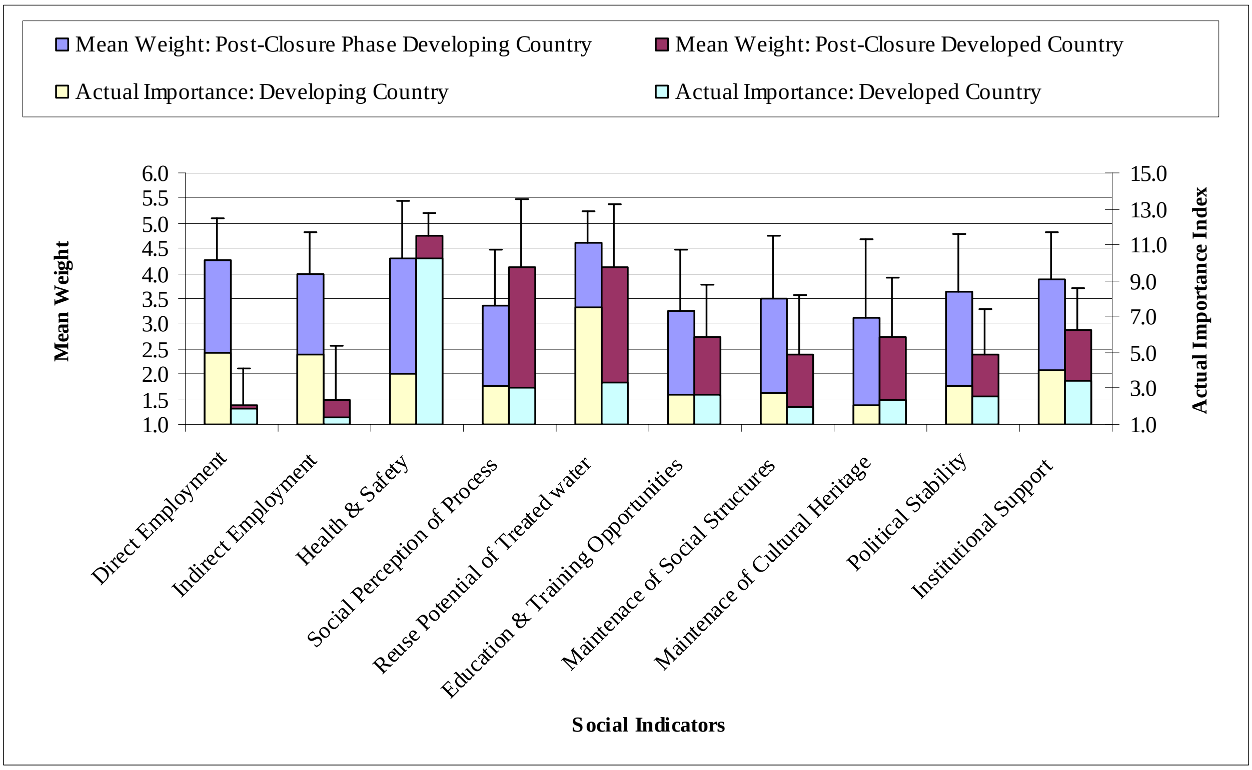

Figure 2.12 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to social indicators for mine water treatment technology (MWTT) development and selection during the post-closure phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= mean Weight Divided by Standard Deviation.

These results showed that social indicators were generally considered more important in a developing country context in the development and assessment of MWTTs, especially during the post-closure phase.

2.4.2.4 Economic Indicators

Developing Country Context

Economic indicators occupy an important position in the assessment of wastewater treatment systems (Bracken, 2005). It is essential that economic indicators, like all other criteria, be assessed on a system-wide basis (Bracken, 2005). The subjects' judgement on the importance of a list of economic indicators during the operational and post-closure phases in a developing country context is presented in **Figure 2.13**. There were significant differences in the rating of the importance of the indicators within the operational phase (ANOVA, df= 5, $p<0.05$) and within the post-closure phase (ANOVA, df= 5, $p<0.05$). Operational and management costs (AII=7.36), capital costs (AII=6.12) and waste disposal costs (AII=5.26) were rated significantly higher than other indicators within the operational phase (ANOVA, $p<0.05$). On the other hand, operational and management costs (AII=7.36) and waste disposal costs (AII=5.61) were rated significantly higher than other indicators during the post-closure phase (ANOVA, $p<0.05$). Licence fees received the lowest rating for both phases. Except for licence fees, cost of spares and decommissioning costs, which were also judged as moderately important during the operational phase, the other economic indicators were overwhelmingly judged to be important (AII>4) for both the operational and post-closure phases of a mine's life.

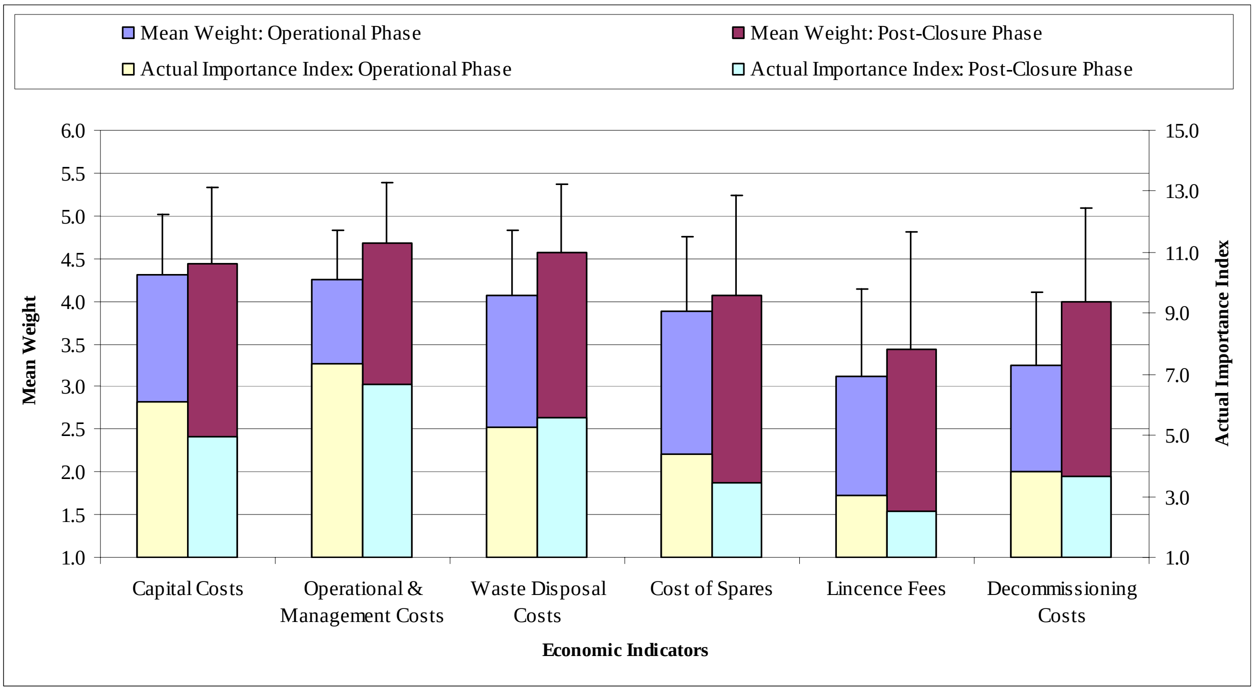

Figure 2.13 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to economic indicators for mine water treatment technology (MWTT) development and selection in a developing country context by 16 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

A comparison of the rating of the indicators during the operational and post-closure phases in a developing country context revealed there was a significant difference (ANOVA, df= 5, $p<0.05$), with capital costs, operational and management costs, licence fees and cost of spares being rated significantly higher during the operational phase (ANOVA, $p<0.05$). The rating of waste disposal costs and decommissioning costs was not significantly different between the two phases (ANOVA, $p>0.05$). It should be noted that although waste disposal costs are part of the operational and management costs, waste disposal costs emerged as being extremely important during the interview process and therefore warranted distinction from operational and management costs during the questionnaire study. It has been observed that cost is a significant indicator in wastewater management (Tsagarakis *et al.*, 2003) and as economic resources are readily accessible during the operational phase of the mine, one would have expected more emphasis to be placed during the post-closure phase, where such resources are expected to be limited.

Developed Country Context

The rating of the economic indicators was significantly different within the operational phase (ANOVA, df= 5, $p<0.05$) and within the post-closure phase (ANOVA, df= 5, $p<0.05$) in a developed country context (**Figure 2.14**). Within the operational phase, operational and management costs (AII= 11.67), waste disposal costs (AII=11.67) and licence fees (AII=7.2) were the most highly rated and were rated significantly higher than capital costs (AII=3.96) and costs of spares (AII=3.91) (ANOVA, $p<0.05$). Capital costs and cost of spares received the lowest ratings. Within the post-closure phase, operational and management costs, waste disposal costs and decommissioning fees were again the most highly rated indicators, while the cost of spares and licence fees received the lowest ratings. The majority of the economic indicators were rated as being important in MWTTs selection during both the operational and post-closure phases.

There was a significant difference in the rating of the indicators during the operational phase and the post-closure phase in a developed country context (ANOVA, df=5, $p<0.05$). Operational and management costs, waste disposal costs and licence fees were rated significantly higher during the operational phase than the post-closure phase (ANOVA, $p<0.05$). While capital costs were not judged to be decisively important during the operational and post-closure phases in a developed country context, the rating was, however, significantly higher during the post-closure phase (ANOVA, $p<0.05$). The cost of spares and licence fees were considered important (AII=4 and AII=7 respectively) during the operational phase but only moderately important during the post-closure phase (AII=3.91 and 3.68 respectively). The importance of licence fees was, however, rated significantly higher during the operational phase than during the post-closure phase (ANOVA, $p<0.05$) while there was no significant difference in the rating of the cost of spares between the two phases (ANOVA, $p>0.05$). Decommissioning costs were considered important during both phases. The importance of licence fees seemed to suggest respect for and effective protection of intellectual property rights in a developed country context. Perhaps, also, waste disposal costs are considered more important in developed countries because it may be much more expensive to dispose of certain categories of wastes correctly.

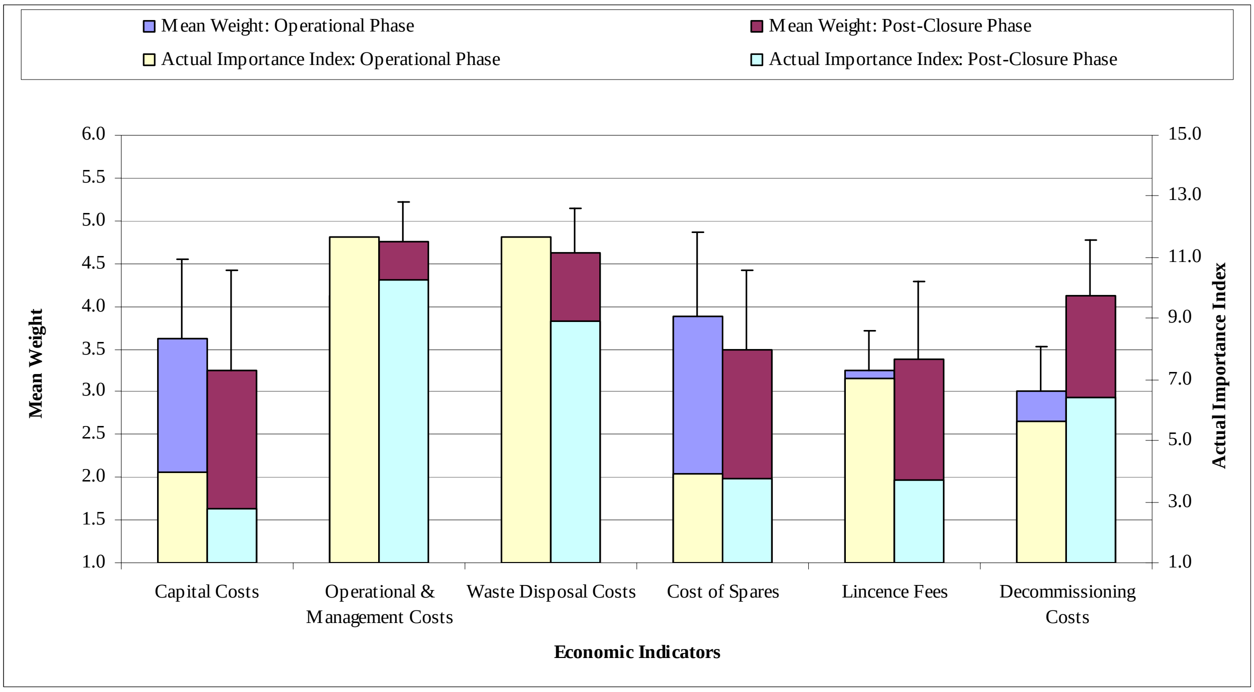

Figure 2.14 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to economic indicators for mine water treatment technology (MWTT) development and selection in a developed country context by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

A significant difference was observed in the rating of the importance of the indicators when the operational phases in the developing and developed country contexts were compared (ANOVA, df= 5, $p<0.05$) (**Figure 2.15**). Four of the six indicators were rated significantly higher in a developed country context than developing country context (ANOVA, $p<0.05$). These were operational and management costs, waste disposal costs, licence fees and decommissioning costs. However, capital costs were rated significantly higher during the operational phase in a developing country context than in a developed country context (ANOVA, $p<0.05$) while the rating of the costs of spares was not significantly different during the operational phase in both contexts (ANOVA, $p>0.05$).

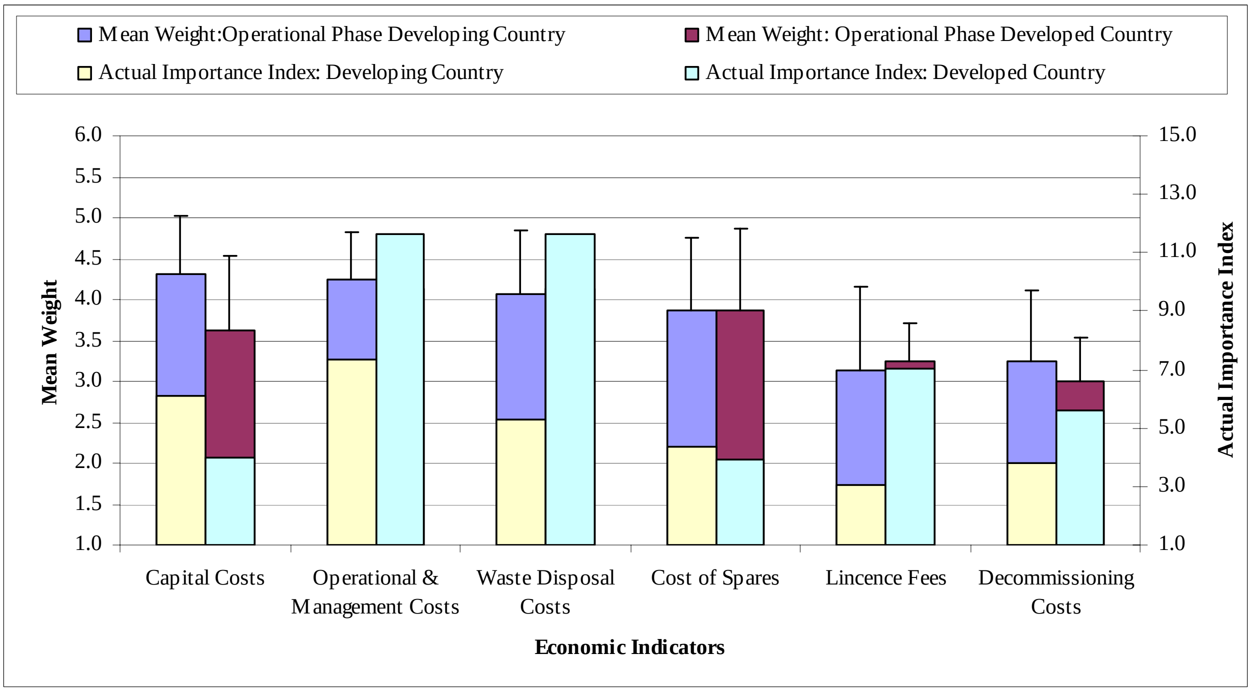

Figure 2.15 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to economic indicators for mine water treatment technology (MWTT) development and selection during the operational phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= mean Weight Divided by Standard Deviation.

A similar pattern was observed in the rating of the indicators when the post-closure phases between a developing and a developed country context were compared (**Figure 2.16**). The rating of the indicators during the post-closure phase was significantly different between the two contexts (ANOVA, df= 5, $p<0.05$). It can be observed that operational and management costs, waste disposal costs, licence fees and decommissioning fees were rated significantly higher during the post-closure phase in a developed country context than developing country context (ANOVA, $p<0.05$) while capital costs was rated significantly higher during the operational phase in a developing country context than a developed country context (ANOVA, $p<0.05$).

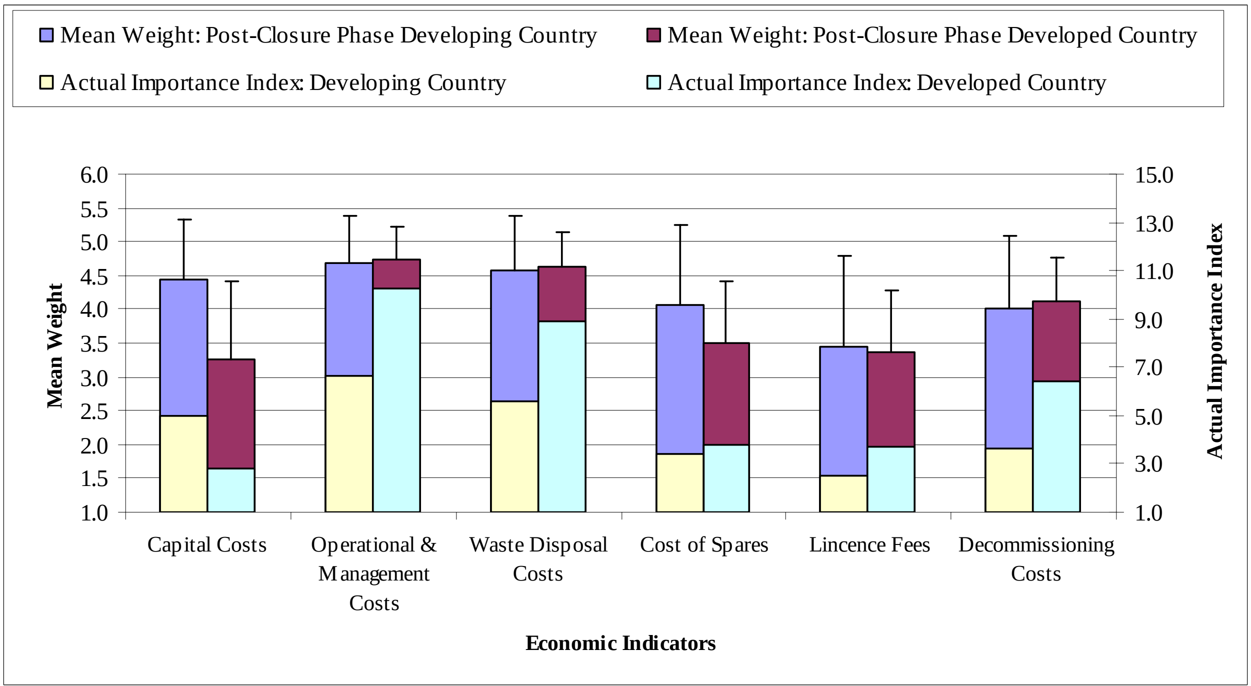

Figure 2.16 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to economic indicators for mine water treatment technology (MWTT) development and selection during the post-closure phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= mean Weight Divided by Standard Deviation.

2.4.2.5 Technical Indicators

Developing Country Context

The technical aspects of a technological system, such as its reliability and performance, may constitute the key to its success and its sustainability (Bracken, 2005). This observation is particularly relevant in a developing country context where technical constraints associated with the deployment and exploitation of technology have resulted in the spectacular failure of many technologies (Dunmade, 2002). The subjects' judgement of the importance of technical indicators for mine waste water treatment evaluation is presented in **Figure 2.17**. The subjects agreed strongly that technical indicators were very important in the assessment of MWTTs. It was observed that 93% of all the technical indicators surveyed were judged to be important during the operational phase while 80% were judged to be important during the post-closure phase. We expected technical considerations to be accorded equal consideration when applying treatment technologies. The difference suggested that more premium is placed during the operational phase, probably as a result of circumventing any punitive measures from regulatory authorities or possibly any negative media exposure that might result from the treatment process during the operational phase. The rating of the indicators was significantly different within the operational phase (ANOVA, df= 14, $p<0.05$) and also within the post-closure phase (ANOVA, df= 14, $p<0.05$).

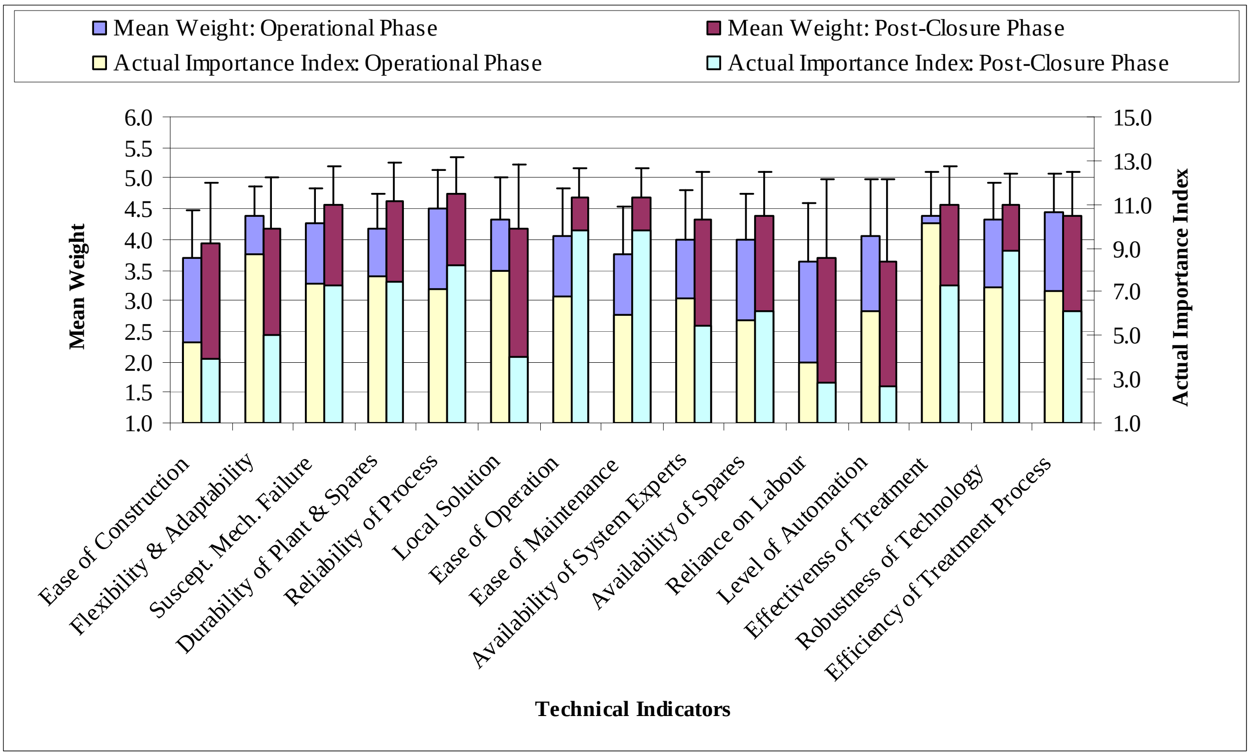

Figure 2.17 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to technical indicators for mine water treatment technology (MWTT) development and selection in a developing country context by 16 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

The most highly rated indicators during the operational phase were effectiveness of treatment (AII=10), flexibility and adaptability (AII=8.8), durability of plant and spares (AII=7.7) and onsite local solution (AII=7.9). These indicators were rated significantly higher than other indicators within the operational phase (ANOVA, $p<0.05$). Reliance on labour received the lowest rating during the operational phase, suggesting perhaps that labour was readily and cheaply available. On the other hand, ease of operation (AII=9.8), ease of maintenance (AII=9.8), robustness of technology (AII=8.9) and reliability of process (AII=8.2) were the most highly rated indicators during the post-closure phase. When combined with the low rating of reliance on labour during the post-closure phase, and possibly, readily available and cheap labour, this seemed to point to the need for passive treatment systems during this phase of mine operation.

The rating of the importance of the indicators was significantly different when the operational and post-closure phases in a developing country context were compared (ANOVA, df= 14, $p<0.05$). 47% of the indicators were rated significantly higher during the operational phase than during the post-closure phase (ANOVA, $p<0.05$). Foremost among these indicators were flexibility and adaptability, onsite solution and effectiveness of treatment. On the other hand, only 20% of the indicators were rated significantly higher during the post-closure phase than during the operational phase (ANOVA, $p<0.05$) and included ease of operation, ease of maintenance and robustness of technology. While the importance of flexibility and adaptability decreased from the operational to the post-closure phase, that of ease of operation, ease of maintenance and robustness of technology increased significantly from the operational to the post-closure phase, perhaps indicating the role passive treatment technologies could play during the post-closure phase.

The importance of approximately 60% of the indicators remained more or less the same during both phases of mine operation. The importance of flexibility and adaptability suggested a proactive approach towards addressing any future changes or adaptations that might be required should new changes be introduced. Such changes may include increased volumes of mine water requiring treatment or new legislation/directives that may be introduced such as more stringent discharge limits.

Developed Country Context

The results obtained for the judgement of the technical indicators for the operational and post-closure phases in a developed country context are presented in **Figure 2.18**. These indicators were generally judged to be highly important during both phases, with 80% of all the indicators being judged highly important during the operational phase, and 47% during the post-closure phase. The rating of the indicators during the operational phase was significantly different (ANOVA, df=14, $p<0.05$), with efficiency of treatment (AII=5), flexibility and adaptability (AII=6.1), reliability of process (AII=5.9) and effectiveness of treatment (AII=5.9) being rated significantly higher than the other indicators while the reliance on labour received the lowest rating. There was also a significant difference in the rating of the indicators during the post-closure phase (ANOVA, df=14, $p<0.05$). Efficiency of process (AII=6.0), reliability of process (AII=5.9), effectiveness of treatment (AII=5.9), and robustness of treatment (AII=5.9) were rated significantly higher than other indicators, with reliance on labour also receiving the lowest rating.

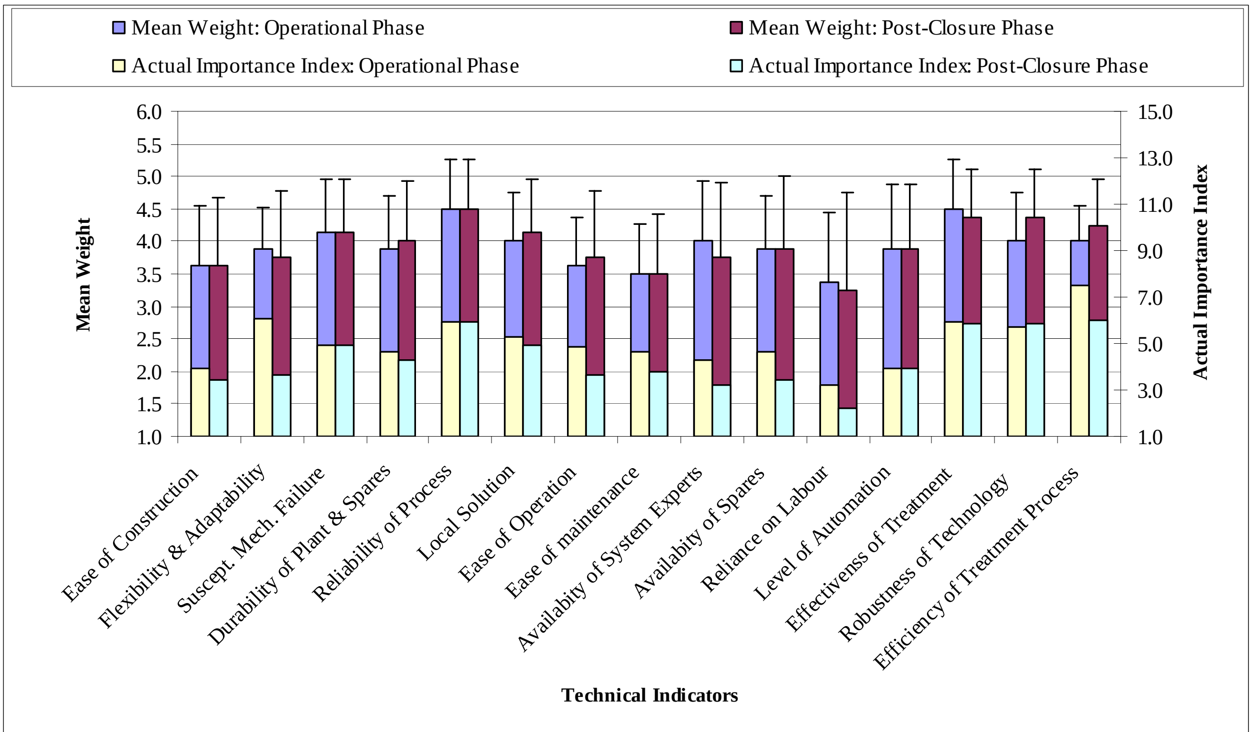

Figure 2.18 Weights on a Likert scale (1-5) and Actual Importance Index scores assigned to technical indicators for mine water treatment technology (MWTT) development and selection in a developed country context by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight divided by Standard Deviation.

A comparison of the rating of the importance of the indicators during the operational and post-closure phases in a developed country context showed there was a significant difference

(ANOVA, df= 14, p<0.05). It was further observed that 47% of the indicators were rated significantly higher during the operational phase than during the post-closure phase (ANOVA, p<0.05). These included flexibility and adaptability, efficiency of treatment, ease of operation, ease of maintenance and availability of system experts. However, the importance of 27% of these indicators, including ease of construction, flexibility and adaptability, reliance on labour and effectiveness of treatment was observed to decrease from the operational to the post-closure phase. In contrast, while the importance of susceptibility to mechanical failure and robustness of technology increased from the operational phase to the post-closure phase, that of the remainder of all the other indicators remained more or less equal during both phases. These observations again seemed to suggest also that passive treatment systems might be the preferred treatment systems at post-closure in a developed country context as well.

There was a significant difference in the rating of the importance of the indicators when the operational phases in a developing and developed country context were compared (ANOVA, df= 14, p<0.05). 80% of the indicators were rated significantly higher in a developing country context (ANOVA, p<0.05) (**Figure 2.19**). Of particular importance were the effectiveness of treatment, efficiency of treatment, local solution, durability of plant and spares, and flexibility and adaptability of process.

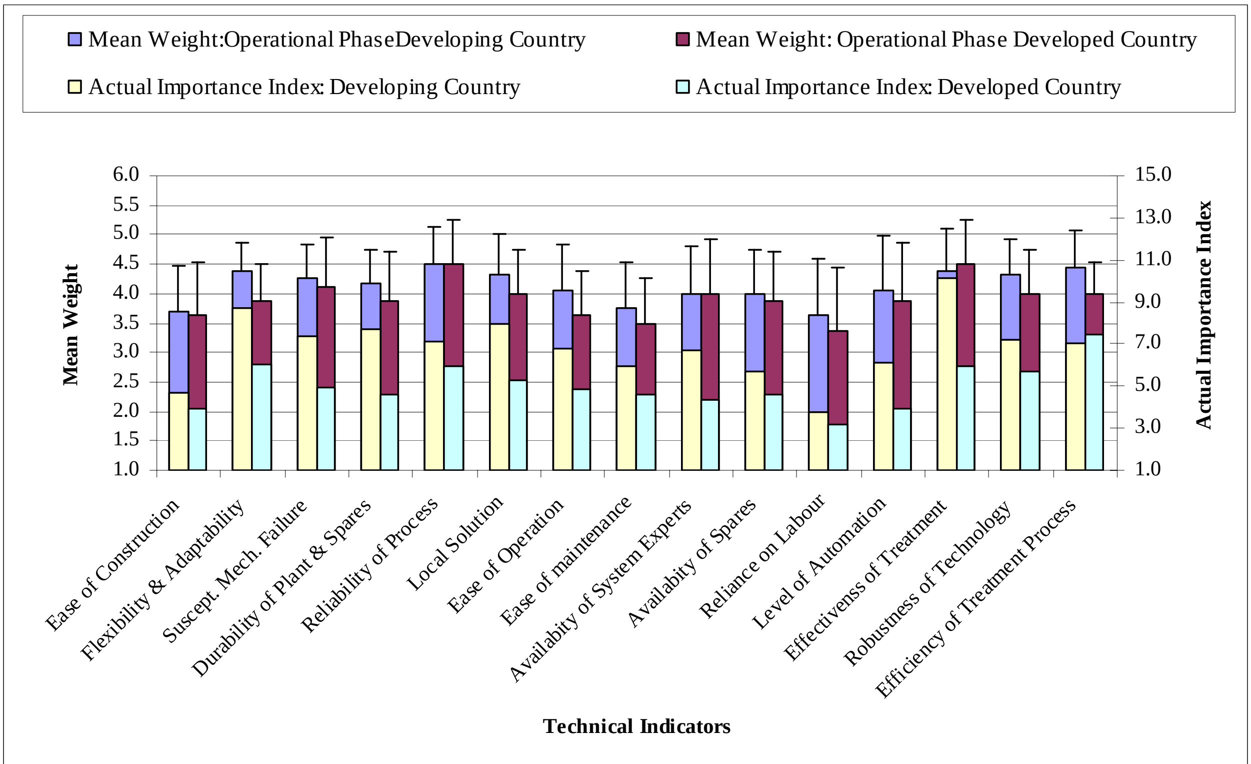

Figure 2.19 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to technical indicators for mine water treatment technology (MWTT) development and selection during the operational phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= Mean Weight Divided by Standard Deviation.

A significant difference was also observed in the rating of the importance of the indicators when the post-closure phases in a developing and developed country context were compared (ANOVA, df= 14, p<0.05). It can also be observed in **Figure 2.20** that 60% of the indicators were rated significantly higher in a developing country than in a developed country during the post-closure phase. The ease of maintenance, ease of operation, effectiveness of treatment and reliability of process were the most highly rated during the post-closure phase in a developing country context, while the reliance on labour and level of automation received the lowest ratings in both the developing and developed country contexts. It can, however, be inferred from these results that technical indicators may be less important in a developed country context than a developing country context. This might be explained by the view that developed countries are generally more technologically advanced and could, in principle, successfully manage and overcome technical problems as these arise. According to Menghistu (1988) cited in Seghezzo (2004), 'the developed world, with less than one third of the world's population, has more than 93% of the world's scientific and technological capabilities, 65% of material resources for development of science and technology, and 99% of scientific and technological information'.

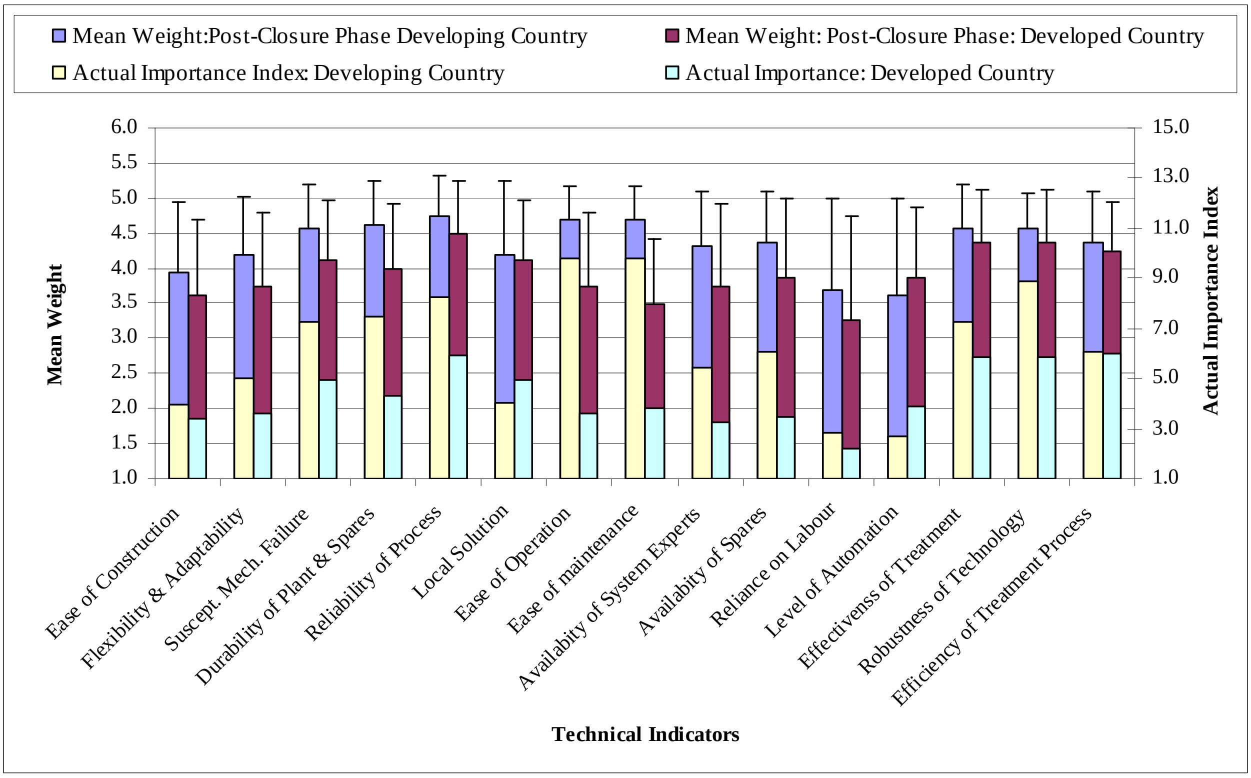

Figure 2.20 Comparison of weights on a Likert scale (1-5) and Actual Importance Index scores assigned to technical indicators for mine water treatment technology (MWTT) development and selection during the post-closure phases in both developing and developed country contexts by 8 professionals from the mining industry. Line bars= Standard Deviations; Actual Importance Index= mean Weight Divided by Standard Deviation.

It should be recalled that technical indicators were, however, rated higher during the operational phase (**Figure 2.3**) and post-closure phase (**Figure 2.4**) in a developed country context when the IBL indicators were compared during the operational and post-closure phases between a developing and a developed country context and no clear reason could be proposed at this stage for this apparent contradiction.

These results raise an important issue in technological relationships between the developing and the developed world and calls into question the sustainability of MWTTs that are developed in the developed world and then transferred and used in the developing nations.

2.4.3 SYNTHESIS OF CRITERIA FOR THE DEVELOPMENT OF A SUSTAINABILITY INDICATOR FRAMEWORK

In the design of decision-support systems, the ranking of criteria by all the stakeholders determines their relative importance for a particular project (Vranes *et al.*, 2001). Subjects' or stakeholders' perceptions may be as important an influence as measured or calculated effects especially with environmental impacts (Bardos *et al.*, 2000; Bardos *et al.*, 2001). One of the salient conclusions from the results obtained in the present study is that the relative importance assigned to some of the indicators surveyed by the subjects cannot be accepted for the sustainability assessment of MWTTs in the South African context. It was obvious that the system currently used in the industry was deficient as it left out a number of key social and environmental criteria. This deficiency may have arisen as a result of the selectors not being aware of the important role of larger environmental and social issues or it might have been a true reflection of the mining industry's perception of sustainability as applied to MWTTs selection. Whatever the case may be, the present scheme did not appear to be in harmony with the sustainability perspectives held by other key players involved in the development and application of MWTTs. Most noteworthy of these was the sustainability perspective promoted by the local and national government regulatory authorities in whose jurisdiction the MWTTs would be implemented. As custodians of the public, their perspective of sustainability is expected to be all-encompassing, with greater emphasis on social, environmental and other developmental issues than was observed in the mining industry.

It is proposed that a satisfactory sustainability assessment system for MWTTs should inherently involve the correlation of the industry's perspective on sustainability with the sustainability perspectives endorsed by official government policy as evidenced in statutory reports. The purpose would be to link the sustainability objectives of private enterprise and public policy to provide a combined function. To achieve this, all the indicators were further aligned and assessed within the broader context of national sustainable development priorities, and their relative importance adjusted based on their perceived degree of importance within this context. Therefore, in order to identify appropriate indicators for possible inclusion in the MWTT development process, and for the assessment and selection of MWTTs, relative weights were derived for the various indicators based on two criteria. The first criterion was the degree to which an indicator was perceived to be important in the mine water treatment industry, as determined by the actual importance scores obtained from the questionnaire study. In this instance, the actual importance values were transformed according to the scheme represented in **Table 2.5.** This scheme was chosen due to its relative simplicity and the ease with which the various AII values could be transformed into relative weights. The second criterion was the degree to which an indicator was represented in four State of the Environment Reports (SoERs) from provinces in South Africa where mining was undertaken.

Table 2.5 A weighting scheme derived from the subjects' judgement for sustainable indicators for mine wastewater treatment technologies assessment.

Actual Importance Index Value	Assigned Weight
< 2	10
>2-4	25
>4-6	50
> 6-8	75
>8-10	100
>10-12	125
>12	150

These provinces include Gauteng Province, Mpumalanga, Kwa-Zulu Natal, and the North West Province. SoERs are statutory reports in terms of the Environmental Conservation Act (Act No. 73 of 1989, Section 13(e)) and the National Environmental Management Act (Act No. 107 of 1998) in South Africa. Among other objectives, SoERs aim to stimulate debate and to raise awareness on important environmental and developmental issues, provide a basis for long-term impacts of decision-making and may be used as management and performance monitoring tools in relation to sustainable development (EMM, 2003). Furthermore, SoERs generally integrate international, regional, national and local socio-economic, political and environmental indicators (EMM, 2003) and were therefore viewed as representing an excellent benchmark for establishing important sustainability indicators in South Africa. While national priorities as documented in SoERs were chosen as a means of addressing the deficiency in the mining industry's system of evaluating and selecting MWTTs, other grounds could also be identified and used depending on the dictates of the local context in which the technologies are being developed or assessed.

An analysis of the SoERs in these provinces produced within the last five years (2000-2005) was carried out and weights on a relative scale of 1 to 6 assigned to the various indicators based on their degree of coverage in the reports. Indicators that were explicitly mentioned in all of the reports analysed were awarded a score of 6, and those that were implied in issues dealt with in all the reports that were perceived to have implications for the sustainability of AMD wastewater treatment were awarded a score of 5. Indicators that were explicitly mentioned in three reports were awarded a score of 4 while those implied in three reports were awarded a score of 3. Indicators explicitly mentioned or implied in one or two reports were awarded a score of 2 while those not mentioned or implied at all, received a score of 1. For each indicator, the final weighting was calculated by multiplying the weights obtained on the industry-based assessment and on the SOER-based assessment, and this represented the maximum possible score that could be assigned for a given indicator, based on the weighting methodology adopted in this study. For future use of the system developed here in different state and mining environments, users could take the results of this study and incorporate their own statutory environmental inputs such as SoERs.

The top 30% of the indicators under each category (i.e. environmental, economic, social and technical) which accumulated the highest score, including those that could be practically integrated in the research and development process, were used to guide the scale-up study of the Rhodes BioSURE Process reported in Chapters 3-7. These are highlighted in bold in the applicable tables discussed below.

Levett (1998) recommended a "fitness-for-purpose" approach in the development of sustainability indicators. Taking a leaf from this approach, a variety of different indicators drawn from the four broad categories, which best address the prevailing circumstances under which the technology is being applied, should be used. This approach was considered to fit well with the context-specificity paradigm. In formulating the proposed framework, this study used the weights assigned during the operational phase in a developing country context with the main objective of illustrating how the framework could be applied. This was based on an examination of all the indicators in all the broad categories, which showed that, except for the environmental category, at least 50% of all the indicators that were judged as important within all the other broad categories were rated significantly higher during the operational phase than during the post-closure phase in a developing country context. In the following sections, although results are presented for industry-derived weights for all broad categories for the operational and post-closure phases in both a developing and a developed country context, the focus falls, however, on the final sets of relative weights formulated from both the industry-derived and SoER-derived weights for the operational phase in a developing country context only.

Environmental Indictors

The results obtained for environmental indicators are presented in **Table 2.6** and **Table 2.7**. Environmental indictors are considered important because of their potential contributions to global energy and climate challenges in the long term. These criteria were generally considered unimportant from the industry's perspective (**Table 2.6**). However, **Table 2.7**, which represents the final weights obtained from the synthesis of industry-derived and SoER-derived weights, shows that the proposed system was sufficiently sensitive to adequately include a range of environmental indicators in the development and selection of MWTTs that had been considered unimportant when the industry-based system was used. It can be observed that quantity of wastes and toxicity of wastes emerged as the most critical environmental indicators that should be taken into consideration in selection of MWTTs and in the scale-up development of the Rhodes BioSURE Process. Both received a score of 300 when statutory/regulatory considerations were considered.

Table 2.6 Industry-derived weights for environmental indicators in developing and developed country context.

Environmental indicators	**Developing country context**		**Developed country context**	
	Operational	**Post-closure**	**Operational**	**Post-closure**
Abiotic depletion	25	25	50	100
Natural resource depletion potential	25	25	25	50
Land area requirement	25	25	50	50
Ecotoxicity potential	25	25	75	75
Phytotoxicity potential	25	25	75	75
Energy depletion potential	25	25	25	50
Global warming potential	25	25	25	25
Acidification potential	10	25	25	25
Nitrification potential	25	25	25	25
Eutrophication potential	25	25	75	25
Bioaccumulation potential	25	25	25	25
Ozone layer depletion potential	10	25	25	25
Photochemical oxidant creation	25	25	25	25
Reuse of raw materials potential	25	25	50	75
Generation of useful by-products	25	50	25	125
Quantity of wastes	50	50	100	100
Toxicity of wastes	50	25	100	100
Effect on biodiversity	10	25	25	25
Potential to attract Pests/Vermin	25	25	25	25
Toxicity of raw materials	25	50	50	100
Aesthetics	25	25	75	50
Odour generation	25	25	50	25
Availability of special waste disposal sites	25	25	75	50
TOTAL SCORE	**580**	**650**	**1100**	**1250**

Table 2.7 Final weights for environmental indictors developed from both industry-derived and SoER-based scores for environmental indicators for operational phase in developing country context.

Environmental indicators	**Operational phase: Developing country context**		
	Industry-based Score	**SoER-based Score**	**Final Score**
Quantity of wastes	50	6	**300**
Toxicity of wastes	50	6	**300**
Natural resource depletion potential	25	6	**150**
Land area requirement	25	6	**150**
Ecotoxicity potential	25	6	**150**
Phytotoxicity potential	25	6	**150**
Energy depletion potential	25	6	**150**
Global warming potential	25	6	**150**
Potential to attract Pests/Vermin	25	6	**150**
Reuse of raw materials potential	25	6	**150**
Eutrophication potential	25	6	**150**
Bioaccumulation potential	25	6	**150**
Photochemical oxidant creation	25	6	**150**
Generation of useful by-products	25	6	**150**
Availability of special waste disposal sites	25	4	**100**
Toxicity of raw materials	25	3	75
Ozone layer depletion potential	10	6	60
Acidification potential	10	6	60
Effect on biodiversity	10	6	60
Nitrification potential	25	2	50
Abiotic depletion	25	2	50
Odour generation	25	2	50
Aesthetics	25	1	25
MAXIMUM POSSIBLE SCORE			**3300**

Other indicators including land area requirements (150), energy depletion (150), potential to attract pests and vermin (150), ecotoxicity (150) and phytotoxicity potential (150) (**Table 2.7**) also emerged as environmental issues that should be considered in the selection of MWTTs and for possible consideration in the scale-up process. It should be recalled that these indicators were generally not considered highly important by the industry-based system (**Table 2.6)**. The emergence of the above indicators as being important seemed to broadly agree with Schmid *et al.* (2002) who observed that "the sustainability of a process relates to energy and raw material use, waste production, process stability/safety and product quality". They maintained that "these factors often translate into a reduction of production costs and then contribute to improved competition, especially in highly regulated countries".

However, from **Table 2.7**, it is evident that other important global indicators such ozone layer depletion, acidification potential and effect on biodiversity did not emerge as being strongly important from this system, perhaps indicating a weakness of the system. This may, however, be traced to the very low importance given to these indicators from the industry's perspective, and it should also be noted that a very low importance score derived from the analysis of statutory/regulatory reports could also result in the low score of an indicator. This suggests that although this system provided a sufficient method of selecting and identifying the most relevant sustainability indicators in the mine water treatment industry than the industry-based system, it should however be applied with some degree of caution on the part of those undertaking the development or selection of MWTTs.

Social Indicators

Table 2.8 shows the industry-derived weights for social indicators in both the developing and developed country contexts while **Table 2.9** shows the final set of weights formulated for the social indicators, derived from both the industry-based scores and SoER-based scores for the operational phase in a developing country context.

Table 2.8 Industry-derived weights for social indicators in developing and developed country contexts.

Social Indicators	Developing country context		Developed country context	
	Operational	**Post-closure**	**Operational**	**Post- closure**
Direct employment	25	50	25	10
Indirect employment	25	50	10	10
Health and safety	50	25	100	150
Social perception	25	25	25	25
Reuse of treated water	50	75	25	25
Education and training	25	25	25	25
Maintenance of social structures	25	25	10	25
Maintenance of cultural heritage	25	25	25	25
Political stability	25	25	25	25
Institutional Support	25	50	50	25
TOTAL SCORE	**300**	**375**	**320**	**345**

Table 2.9 Final weights derived for social indicators from both industry-based scores and SOER-based scores for operational phase in developing country context.

Social Indicators	Operational phase: Developing country context		
	Industry-based Score	**SoER-based Score**	**Final Score**
Health and safety	50	6	**300**
Reuse of treated water	50	5	**250**
Indirect employment	25	6	150
Direct employment	25	6	150
Education and training	25	6	150
Maintenance of cultural heritage	25	6	150
Maintenance of social structures	25	2	50
Social perception	25	1	25
Political stability	25	1	25
Institutional Support	25	1	25
MAXIMUM POSSIBLE SCORE			**1175**

Social criteria were generally considered unimportant from the industry's perspective. An examination of **Table 2.8** and **Table 2.9** shows that social indicators that had received low weights from the industry-based system received higher weights when the SoER values were included. The new system was generally more sensitive and provided a much more inclusive method of selecting MWTTs that took social sustainability into consideration. With respect to the social criterion, health and safety considerations (300) and the reuse of treated water (250) (**Table 2.9**) emerged as top indicators that should be included in the selection of MWTTs and that should be integrated into the scale-up process. Both direct and indirect employment and education and training opportunities also emerged as critical social indicators that should be considered in selecting MWTTs. Each of these indicators received a final weight of 150 (**Table 2.8**), up from a weight of 25 when rated on the industry-based system alone (**Table 2.7**). Indicators such as employment, education and training are generally important in a developing country context because of the high unemployment and high illiteracy rates. The emergence of maintenance of cultural heritage as also being important, though surprising in the context of MWTTs, could indeed be valid as socio-cultural issues have been identified as critical sustainability indicators in the assessment of wastewater treatment undertakings in general (Kvarnström *et al.*, 2004). The importance of the maintenance of social structures still remained low, probably because MWTTs generally do not require extremely large expanses of land (except for wetlands), although the impacts of mine water treatment may also be spatially extensive. This implies that the chances of any large-scale disruption of social structures in the implementation of MWTTs was minimal and therefore was not considered as critically important compared to other large scale projects. On the other hand, institutional support, which was expected to be critically important, emerged as not being important. No obvious reason could be ascribed for this observation, although it may be assumed that institutional support structures may be readily available. In addition, institutional arrangements are not adequately addressed in SoERs.

Economic Indicators

The results obtained for the economic indicators are presented in **Table 2.10** and **Table 2.11.** Waste disposal costs, capital costs and operational and management costs emerged as the top indicators that could be used to improve the sustainability of technologies during bioprocess development and the selection of MWTTs. Waste disposal costs received the highest score (300) (**Table 2.11**). The cost of spares was also considered important. These observations were largely expected as economic indicators emerged as being critically important from the industry's perspective. However, since economic sustainability involves the entire lifecycle cost analysis (Dunmade, 2002), licence fees and decommission costs were not expected to emerge as being unimportant, especially since these costs could be high.

Table 2.10 Industry-derived weights for economic indicators in developing and developed country context.

Economic Indicators	**Developing country context**		**Developed country context**	
	Operational	**Post-closure**	**Operational**	**Post- closure**
Capital costs	75	50	25	25
Operation & management cost	75	75	125	150
Wastes disposal cost	50	50	125	100
Cost of spares	50	50	50	25
Licence fees	10	25	75	25
Decommissioning fees	25	25	50	100
TOTAL SCORE	**285**	**275**	**450**	**425**

Table 2. 11 Final weights for economic indicators derived from both industry-based scores and SOER-based scores for operational phase in developing country context.

Economic Indicators	**Operational phase: Developing country context**		
	Industry-based Score	**SoER-based Score**	**Final Score**
Wastes disposal cost	50	6	**300**
Capital costs	75	2	**150**
Operational & management cost	75	2	**150**
Cost of spares	50	2	100
Decommissioning fees	25	1	25
Licence fees	10	1	10
MAXIMUM POSSIBLE SCORE			**735**

It was expected that licence fees would score high from the industry's perspective since the element of cost was generally considered important. This suggests that the costs involved were relatively small or that the observance of intellectual property rights was not particularly high priority in a developing country context.

Technical Indicators

The results for technical indicators are presented in **Table 2.12** and **Table 2.13**. It can be observed from **Table 2.13** that flexibility and adaptability (300) and efficiency of treatment process (300) emerged as critical technical indicators that should be considered in the selection of MWTTs and that should be considered in the scale-up process.

Table 2.12 Industry-derived weights for technical indicators in developing and developed country context.

Technical Indicators	**Developing country context**		**Developed country context**	
	Operational	**Post-closure**	**Operational**	**Post- closure**
Ease of construction	50	25	50	25
Flexibility and adaptability	100	50	75	25
Susceptibility to mechanical failure	75	75	50	50
Durability of plant & spares	75	75	50	50
Process reliability	75	100	150	150
Onsite/local solution	50	50	50	50
Ease of operation	50	125	75	75
Ease of maintenance/replacement of part	75	125	75	75
Local availability of system experts	50	50	50	25
Availability of spares	50	50	50	50
Reliance on labour	25	50	25	10
Level of automation	25	25	50	50
Effectiveness of treatment	50	75	150	100
Robustness of technology/process	75	125	50	100
Efficiency of process	75	50	100	100
TOTAL SCORE	**900**	**950**	**1050**	**935**

Table 2.13 Final weights derived for technical indicators from both industry-based scores and SOER-based scores for operational phase in developing country context.

Technical Indicators	**Operational phase: Developing country context**		
	Industry-based Score	**SoER-based Score**	**Final Score**
Flexibility and adaptability	100	3	**300**
Efficiency of process	75	4	**300**
Effectiveness of treatment	50	4	**200**
Ease of operation	50	4	**200**
Process reliability	75	2	150
Ease of maintenance/replacement of part	75	2	150
Robustness of technology/process	75	2	150
Durability of plant & spares	75	1	75
Susceptibility to mechanical failure	75	1	75
Local availability of system experts	50	1	50
Availability of spares	50	1	50
Onsite/local solution	50	1	50
Ease of construction	50	1	50
Level of automation	25	1	25
Reliance on labour	25	1	25
MAXIMUM POSSIBLE SCORE			**1850**

Other critically important indicators included effectiveness of treatment (200) and ease of operation of the technology (200). Process reliability, the ease of maintenance/replacement of spares, and the robustness of technology were also considered important, with each obtaining a final weight of 150 (**Table 2.13**). These observations were largely expected. However, a number of technical indicators received lower scores than expected. These included durability of plant and spares, susceptibility to mechanical failure, local availability of system experts, availability of spares, ease of construction and reliance on labour (**Table 2.13**).This could be attributed to an improved technological environment, where technical skills and expertise, information and spares were readily available and affordable, although this might be different in other developing countries.

The method used to synthesize industry and SoER indicators in MWTT prioritisation provides both expected and unexpected, but nevertheless, credible outcomes that could be understood in terms of overall sustainability thinking. However, for this to be functionally applicable in either the selection or development of MWTTs or in the development of public policy, it would be necessary to present the methodology in a workable structure. In dealing with this, a Decision- Support System was developed which is described in the following section.

2.4.4 CONCEPTUAL DECISION-SUPPORT SYSTEM FOR MINE WASTEWATER TREATMENT TECHNOLOGY SELECTION AND DEVELOPMENT.

A concept, linking an industry-perspective of sustainability with statutory/regulatory sustainability requirements in conjunction with quantitative elements was developed in the preceding sections to provide a semi-quantitative basis for a Sustainability Indicator Framework for the development and selection of MWTTs. In the Decision-Support System proposed in **Figure 2.21,** the point of departure for the technology development and selection exercise is the correct articulation of the treatment objectives (Step 1). At this stage, the purpose of the treatment, the nature of the mine water requiring treatment, the quantity of the mine water requiring treatment, the degree of effectiveness of treatment and the duration of treatment, in addition to any other objectives, are spelled out. Based on this, all technologies that could potentially fulfil the treatment objectives are identified (Step 2). This could also include technologies at laboratory-scale or bench-scale or even those still at the conceptual phase of development. Key industry-based and statutory/regulatory-based sustainability indicators such as SoERs are identified (steps 3a & b) and core sustainability indicators are then developed using the same method applied in this chapter. All the potential technologies are then subjected to a rigorous technology screening process based on a synthesis of the key industry-derived and statutory/regulatory based sustainability criteria (Step 4).

In the case of the development of new technologies, the key indicators that emerge would inform the technology development process. The expected outcome of the Decision-Support System is the development or selection of technologies based on sound sustainability objectives using context-specific sustainability indicators. It should be noted that while the industry score range would not depend on location, the SoER priorities would, and therefore, it would be relatively simple to modify the current system to suit other countries or regions. This would be achieved by simply reviewing the local sustainability priorities for the region where the development or selection of the MWTT is being undertaken.

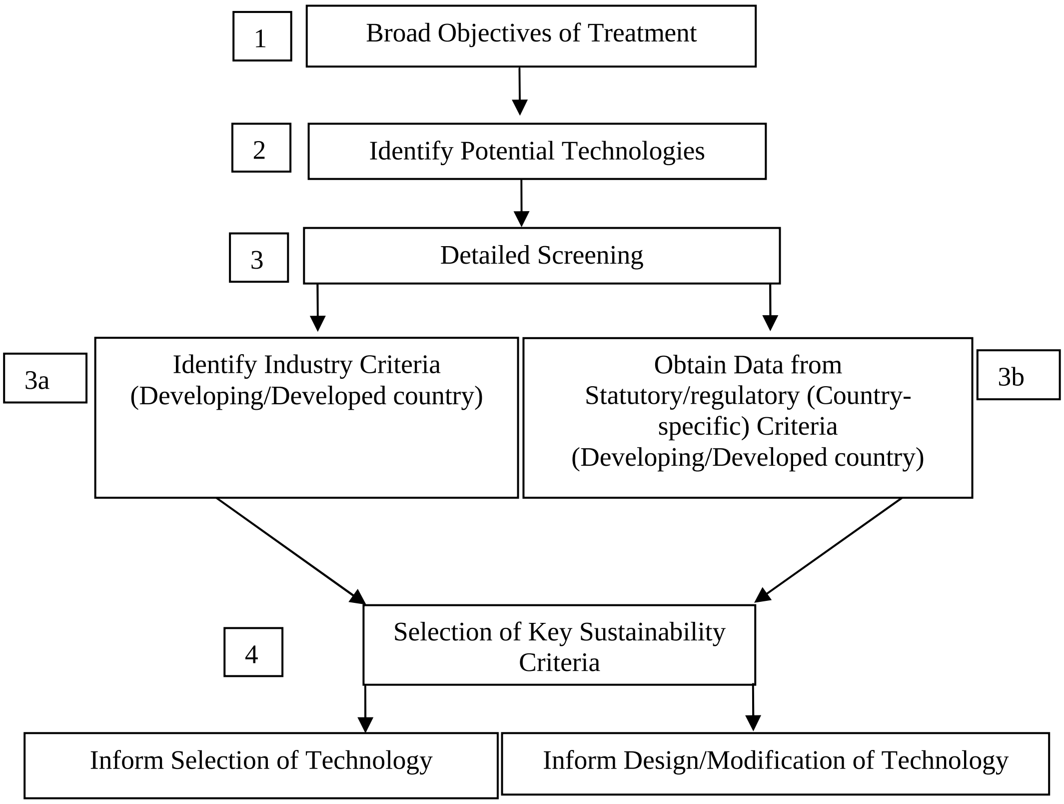

Figure 2.21 Decision-Support System for bioprocess technology development and choice-of-technology selection for the mining industry.

2.5 CONCLUSIONS

It was found that no formalised decision-support tool integrating the IBL principles existed to support the evaluation of MWTTs, bringing to the fore the question of sustainability of the technologies that were chosen using the approaches currently being employed in the mining industry. The current approach was found to be predicated on informal bases, and laid emphasis mainly on economic and technical indicators, with a limited number of environmental and social indicators taken into account in the decision-making process. It has emerged from this study that an overwhelming need exists for the development of an effective formalised decision-support tool for the assessment of MWTTs within the South African mining industry. Although no consistent set of criteria for the selection of MWTTs were proposed by the subjects for the operational and post-closure phases of a mine's life, it emerged that the criteria developed for the operational phase should be focused on an active in-house treatment bias, and along a passive treatment or an out-sourcing basis for the post-closure phase. In other words, during the operational phase, the selection of MWTTs should be directed towards active treatment systems, mainly operated by the mine itself, while during post-closure phase, the mine water treatment function should be directed towards passive treatment systems and/or those outsourced to third party operators. Furthermore, decision-making on the technology selection process appeared to be tailored towards meeting specific treatment objectives, and centred on short-term, rather than long-term goals, therefore implying a level of unsustainability in current approaches. It was also found that selection criteria differed between a developing and a developed country context largely as a result of the different needs and prevailing socio-economic conditions in different regions. This indicated that technology development should take into account the different needs of application in the developing and developed world contexts.

The findings seemed to broadly agree with the assertion that short-term economic interests continue to propel technological innovations that would generally be construed as "meaningless or even negative" within the requirements of sustainable development thinking (Seghezzo, 2004). However, from the subjects' judgment of the importance of the various indicators in the mine water treatment industry, and the degree of treatment of the various indicators in various SoERs, core indicators have been identified and relative weights developed incorporating both perspectives (**Table 2.14**).

This represented a synthesis of the mining industry's perspective of sustainability with that of the South African statutory/regulatory authority in the development and selection of MWTTs. These may contribute meaningfully in guiding MWTT development and assessment of the sustainability of different treatment options in South Africa. A "fitness-for- purpose" approach is recommended in the use of the indicators developed here, whereby specific indicators are selected from each IBL category for application in any given situation, depending on the treatment objectives and the specific requirements of the local context. The dearth of appropriate criteria through which the sustainability of different systems or technologies can be quantified has been given as one of the main obstacles that delay people, companies, institutions and governments from adopting more sustainable solutions (Lettinga *et al.*, 2001). The findings of this study therefore represent a first attempt at collating relative weights for a set of indicators from the mining industry's perspective and from a statutory/regulatory perspective that may guide the assessment and research and development of MWTTs in the mine water treatment industry in South Africa. This study is also important in that the concept, the methodology used and the results obtained may be adapted to guide businesses in making informed decisions on technological choices, especially in instances where such businesses are contemplating investments in novel technologies.

Table 2.14 Summary of top ranked indicators to be considered where mine water treatment technology (MWTT) development is targeted (Weight ≥ 100).

Environmental Indicators	Social Indicator	Economic Indicators	Technical Indicators
Quantity of wastes	Health and safety	Wastes disposal cost	Flexibility and adaptability
Toxicity of wastes	Reuse of treated water	Capital costs	Efficiency of process
Natural resource depletion potential	Indirect employment	Operational & management cost	Effectiveness of treatment
Land area requirement	Direct employment	Cost of spares	Ease of operation
Ecotoxicity potential	Education and training		Process reliability
Phytotoxicity potential	Maintenance of cultural heritage		Ease of maintenance/replacement of part
Energy depletion potential			Robustness of technology/process
Global warming potential			
Potential to attract Pests/Vermin			
Reuse of raw materials potential			
Eutrophication potential			
Bioaccumulation potential			
Photochemical oxidant creation			
Generation of useful by-products			
Availability of special waste disposal sites			

The study on MWTT indicators reported here was motivated, at least partially, by the need to develop guidelines that incorporate sustainability requirements for the scale-up undertaking of the Rhodes BioSURE Process. While it may not be realistic to systematically include all the indicators identified in this study in the technology development process, the importance of identifying and developing relative weight for such indicators cannot be overemphasised. The onus on deciding how and to what extent to apply these indicators in development and selection of technologies therefore lies with individual stakeholders, which include water treatment engineers, researchers, technology developers, environmental practitioners and consultants. For the purpose of the scale-up undertaking of the Rhodes BioSURE Process, the Sustainability Indicator Framework developed here provided general guidelines that both confirmed and altered preliminary assumptions and focussed the technology development undertaking as described below. The following points emerged:

1. In terms of the Sustainability Indicator Framework findings, requirements for active treatment of mine water and post-closure operation appeared to be contradictory. In this regard, the Rhodes BioSURE Process, being an active treatment process might not be suitable for application in the post-closure phase. However, since the selection of MWTTs for post-closure operations may also be directed towards a third party operator on an out-sourced basis, and the use of PS as a low-cost carbon source render it viable as a post-closure treatment technology from an out-sourced perspective. In this case, a public utility operator that generates PS on a continuous basis could conveniently provide such a contractual function in the post-closure phase. This, together with the low cost function therefore indicates the need to evaluate the suitability of established reactor configurations, used conventionally in sewage treatment operation, for possible application in the scale-up of the Rhodes BioSURE Process;
2. The economic sustainability component, which focused on capital, operational and management and waste disposal costs, might also be addressed in the scale-up of the Rhodes BioSURE Process through the evaluation of waste disposal routes and the possible use of standard sewage treatment infrastructure;
3. Health and safety considerations and the reuse of treated effluent for economic purposes which emerged as critical social indicators, and that could improve the social sustainability component of the scale-up undertaking, might be integrated through the effective polishing of the treated effluent to requisite reuse standards. An evaluation of the use of well-established wastewater treatment technologies such as the biological trickle filter, might be investigated for polishing purposes. The integration of downstream revenue generation activities alongside the mine water treatment process from the possible reuse of the polished treated effluent would further contribute to the social sustainability component of the technology;
4. The technical sustainability requirement, embodied in flexibility and adaptability, efficiency and effectiveness, and ease of operation, might be improved in the scale-up undertaking of the Rhodes BioSURE Process in a number of ways. The possible use of proven and well-established sewage treatment infrastructure might improve this component. However, the advantages of the strong linkage of the process to sewage treatment facilities paradoxically also limits its application in terms of flexibility and adaptability as this limits its application outside the sewage treatment environment. This therefore suggests the need for the investigation of alternative complex electron donor sources (organic wastes) for the process which would enable the application of the technology to be uncoupled from the sewage treatment environment. An improved understanding of the principles underlying the hydrolysis of PS within the system might provide further avenues to improve efficiency and effectiveness of treatment through process optimisation;

5. The improvement of the environmental sustainability component, embodied through improving quantity of wastes and toxicity of wastes may be achieved in the scale-up undertaking through improved PS hydrolysis (waste conversion), and through the conversion of sulphide to a more stable waste stream suitable for disposal.

The following chapters of this report deal with the scale-up development of the Rhodes BioSURE Process at bench-, pilot- and technical-scale investigations and with the process development undertaking largely predicated by aspects of the findings which have been outlined above.

3 REACTOR CONFIGURATION

3.1 INTRODUCTION

Previous research undertaken over several years at EBRU had focused on the use of complex carbon substrates as readily available electron donor and carbon sources for biological sulphate reduction. It had been shown that complex carbon substrates such as tannery effluent and PS could be used effectively as electron donors in sulphate reduction and that the rate of PS hydrolysis was enhanced in the RSBR configuration (Molepane, 1999; Whittington-Jones, 2000; Corbett, 2001; Enongene, 2003; Molwantwa *et al.*, 2004).

A linkage between the enhanced hydrolysis of complex carbon substrate and increasing sulphide concentration gradients, observed in the anaerobic compartments of tannery ponding systems, had been proposed by Dunn (1998). This was apparently confirmed in follow-up studies of sulphate-reducing systems conducted at laboratory-scale using variants of single and multi-stage prototype RSBRs (Whittington-Jones, 2000; Enongene, 2003) and at preliminary pilot-scale at Grootvlei Mine by Corbett (2001) using a modified multi-stage process integrating a lateral flow RSBR and an ABR. A number of other studies had indicated an enhancement of the hydrolysis of organic substrates under sulphate reducing compared to methanogenic systems (Kim *et al.*, 1997; Pareek *et al.*, 1998; Molwantwa, 2002).). However, a more recent study, designed to collect quantitative data on the rates of hydrolysis of PS under acidogenic, methanogenic and sulphidogenic conditions, found no significant difference in the rates of hydrolysis (Ristow *et al.*, 2004). This investigation had been carried out in completely mixed reactors compared to the RSBR system used in the previous studies which suggested that the reactor configuration environment may be important in determining PS hydrolysis rate measurement. Several other factors have also been shown to influence the rate and degree of hydrolysis of complex organic biopolymers (Raunkjær *et al.*, 1994). These include the makeup of the substrate, the species of microorganisms associated with the inoculum and the concentration and activity of hydrolytic enzymes present (Eastman and Ferguson, 1981; Levin *et al.*, 1985); COD (Raunkjær *et al.*, 1994); loading rates, hydraulic retention times (HRT), alkalinity, sludge retention time and mixing (Gujer and Zehner, 1983; Banister and Pistorius, 1998; Perot *et al.*, 1988), pH and temperature (Gujer and Zehner, 1983; Banerjee *et al.*, 1998; Perot *et al.*, 1988; Teichgräber, 2000) and, including reactor design (Enongene, 2003).

Of these factors, the spatial distribution of reactants within the reactor environment itself is of importance in the control and optimisation of treatment systems that exploit microbial technology for the bioremediation of AMD (Johnson, 1995). In design of biological reactors, the primary goal is to maximise contact between the substrate and biocatalyst in order to optimise the reactions occurring between them (Enongene, 2003). Reactor architecture may contribute in a number of ways to influence the hydrolysis/solubilisation of PS under sulphidogenic conditions. This might not only include optimisation of contact gradients that may exist in the reactor and between reactants as observed in completely mixed systems, but also to maximise reaction potential through different concentration gradients of reactants, intermediates and products that may be set up in these systems. Factors involved would include alkalinity, sulphide concentration, enzyme activity and, possibly, variable bacterial activity. However, a systematic comparison of the performance of enhanced sulphidogenic hydrolysis of PS in different reactor configurations has not been reported.

The need to identify, quantify and then to incorporate sustainability requirements into the MWTT development process investigated in Chapter 2 had provided a strong indication that proven equipment design which is in common use in the sewage treatment industry be used in the scale-up development of the Rhodes BioSURE Process. This would be particularly important in the developing world context where long range sustainability would depend, in considerable measure, on the capability of the utility provider. Issues of importance include ease of operation of technology, robustness of technology, availability of spares, ease of construction and maintenance of technology and process reliability.

However, these conditions were not met in the Grootvlei pilot study in the scale-up development of the Rhodes BioSURE Process. Here, novel reactor designs had been used including a lateral flow RSBR and a baffled reactor in order to establish a dual stage separating the hydrolysis and sulphate reduction steps (**Figure 1.3**). The lateral flow RSBR was a novel design concept which had been based on the observed performance of the recycling sludge beds in tannery ponds shown in **Figure 1.1** (Whittington-Jones, 2000). This unit consisted of three continuous partitions, with the lower meter of each partition forming a settling valley. Settled sludge was collected sequentially from each of the valleys and combined with mixed feed of mine water and PS while effluent flowed by gravity into the baffled reactor. The baffled reactor was configured with four separate compartments (Corbett, 2001). Although relatively recently investigated in wastewater treatment applications, baffled reactors have been reported to integrate granular, mixed anaerobic cultures in separate compartments, enabling partial separation of acidogenesis and methanogenesis, higher resilience to hydraulic and organic shock loads, longer biomass retention times, lower shock loads and generally offering high treatment rates (Grobicki and Stuckey, 1990; Nachaiyasit and Stuckey, 1995; Nachaiyasit and Stuckey, 1997; Barber and Stucky, 1999 cited in Foxon *et al.*, 2004; Foxon *et al.*, 2004). Although Corbett (2001) had demonstrated impressive results for overall sulphate reduction in the preliminary pilot scale-up study of the Rhodes BioSURE Process at Grootvlei Mine (**Figure 1.3**) using these novel reactor systems, in the light of the sustainability requirement identified, and relating to the advantages of well-established technologies used by utility operators, it was considered necessary to re-evaluate the performance of the process using conventional reactor configurations, and hence this required a return to bench-scale studies in the first instance.

Both scale-up and scale-down studies are invaluable concepts in investigating and overcoming a wide range of challenges involved in converting laboratory and other small-scale piloting results to operate successfully at full scale (Scott *et al.*, 1998). The need for scaling may arise at two independent occasions including when a new process is scaled-up and when an existing process is subject to modification (Zufferey, 2006). Pilot plants, as instruments in scale-up studies, integrate similarity relationships that are judged to be key engineering challenges in the process such as heat and mass transfer, process kinetics, reactor residence time, flow characteristics, distribution of residence times, and process dynamics (Calderone, 1994). However, although similarity relationships are fundamental in scale-up studies, Reuss (1993) observed that the concept can hardly be applied because critical similarity states such as geometry, kinematics and dynamics are virtually impossible to maintain when going from laboratory to large scale operation. Implicit in this observation therefore, is the probability of new or unexpected outcomes occurring at pilot-scale, which may necessitate other scale-down studies of an exploratory or confirmatory nature. Trille (1986) had noted the value of subsequent scale-down procedures as means of improving an already functional process.

While scale-up models are standard practice in process development, Simoglou *et al.* (2001) stated that scale-down is an unusual concept since most development work begins from small-scale. However, scale-down models provide an immediate approach to the rational scaling of reactors whereby many parameters may be tested more rapidly and less expensively than at the pilot-scale (Knorr, 2005). Scale-down studies offer experimental systems at a smaller scale that replicate the heterogeneity in environments existing at larger scale and therefore provide further opportunities in which proposed process modifications for an existing operational process may be evaluated (Shuler and Kargi, 1992 cited in Knorr, 2005). Such scale-down studies have also been demonstrated as a viable means of improving and optimising large-scale processes (Oosterhuis *et al.*, 1985; Amanullah *et al.*, 2001; Enfors *et al.*, 2001; Onyeaka *et al.*, 2003; Papagianni *et al.*, 2003; Delvigne *et al.*, 2006).

3.2 RESEARCH OBJECTIVES

The objective of this study was thus to investigate the hydrolysis of PS and sulphate reduction in a number of reactor configurations in common use in sewage treatment. Reactors selected for this study included the Dortmund tank reactor, the UASB and the continuous stirred tank reactor (STR). These were to be modified to enable sludge recycle and the establishment of sulphide gradients within the reactors, which had been proposed to be important considerations by previous workers. These findings would be used to inform selection of appropriate reactor design configuration for the subsequent scale-up development of the Rhodes BioSURE Process. Specifically, the following questions needed to be addressed:

1. Could the process work effectively in reactor designs other than those used in the initial studies?
2. If so, which of the reactor configurations in use in sewage treatment and to be investigated would provide the best performance?

3.3 MATERIALS AND METHODS

3.3.1 Reactor Systems and Experimental Design

Bench-scale fed-batch experiments on PS solubilisation were conducted in three different reactor designs, a modified Dortmund-type upflow recycling sludge bed reactor (RSBRd), a Column UASB-type upflow recycling sludge bed reactor (RSBRc) and an STR without sludge recycle. The reactors were set up as follows:

3.3.1.1 The Upflow Dortmund-type Upflow Recycling Sludge Bed Reactor

The RSBRd (diameter 46 cm, height 35 cm, working volume 20 ℓ) was constructed from 5 mm Perspex (**Figure 3.1**). A lid was fitted with three 20 mm ports. Two of these ports were located at the centre; one being an inlet port for the addition of fresh feed and the other an inlet port for recirculation of return feed. The third port, located very close to the two at the centre, led into the space immediately outside the inner stilling column and was used for drawing samples. The feed port was sealed with a rubber stopper, which could be removed when required, while the inlet port for the recirculation was fitted with a short cylindrical Perspex pipe over which the tubing used for recirculation could be tightly secured. These two ports led directly into an inner cylindrical stilling column also made of Perspex, with a diameter of 10 cm and a height of 20 cm, supported in position by a sheet of Perspex anchored at an angle of 60^{o} on the inner side of the surrounding Perspex body. Two outlets with valves were installed, the first one at a distance of 5 cm below the overflow point at the top of the reactor and the second at the bottom of the reactor. The outlet at the top of the reactor was designed to collect the overflow for recirculation while the bottom outlet was designed to collect the particulate organic matter that settled at the bottom of the reactor for recycle as well.

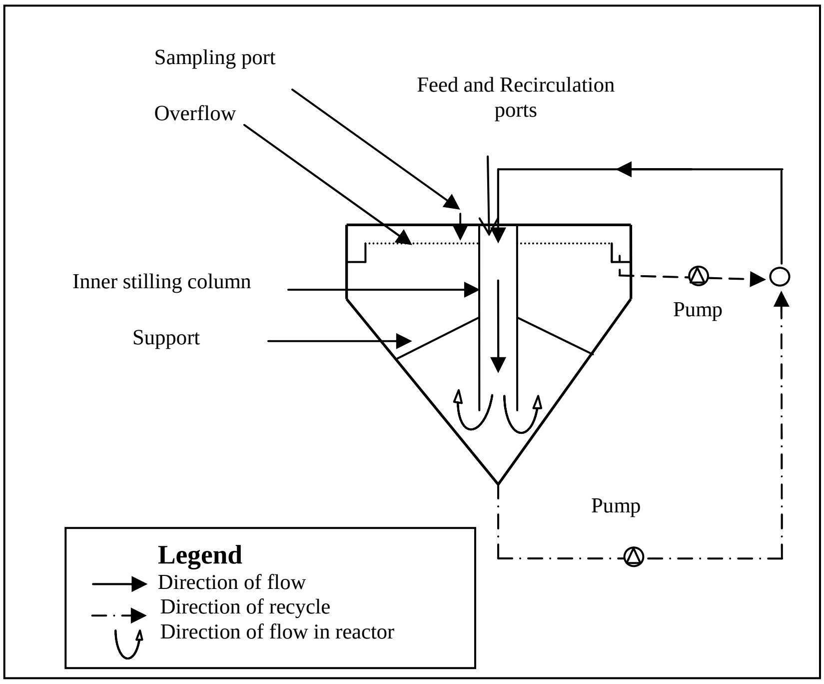

Figure 3.1 Schematic illustration of the Dortmund-type Upflow Recycling Sludge Bed Reactor (RSBRd) used in the bench-scale study.

The settled particulate matter drawn at the bottom of the reactor could be pumped and combined with the outflow at the top, and the mixture could be recirculated to the reactor inlet. Oxygen impermeable Tygon® tubing was used for recycling. A Watson Marlow 504S peristaltic pump with variable speed control was used for recirculation of both the settled particulate organic matter at the bottom of the reactor and the overflow at the top of the reactor. Marprene® tubing was used in the pump head. The reactor was completely sealed with vacuum grease to exclude air and the head space was sparged with nitrogen gas to maintain anaerobic conditions and prevent surface floating sulphur film formation.

3.3.1.2 The Column Upflow UASB-type Recycling Sludge Bed Reactor

The RSBRc was constructed in 5 mm cylindrical Perspex (diameter 10 cm, height 50 cm, working volume 3.5 ℓ) and fitted with a Perspex base-plate and lid (**Figure 3.2**). The lid had a single inlet port located at the centre, fitted with a T-piece providing for delivery of fresh feed and also the combined recirculation of the overflow and the settled particulate organic matter drawn from the bottom of the reactor. This port led directly to an inner Perspex pipe (0.1 cm in diameter with a height of 45 cm) extending to 5 cm from the bottom of the reactor. The outlet port was located 2 cm below the top of the reactor. A second outlet port at the bottom of the reactor provided for the recirculation of settled particulate matter while a sampling port was located 15 cm from the top of the reactor from which samples were drawn by syringe. The tubing and the pump system used was similar to that operated on the RSBRd.

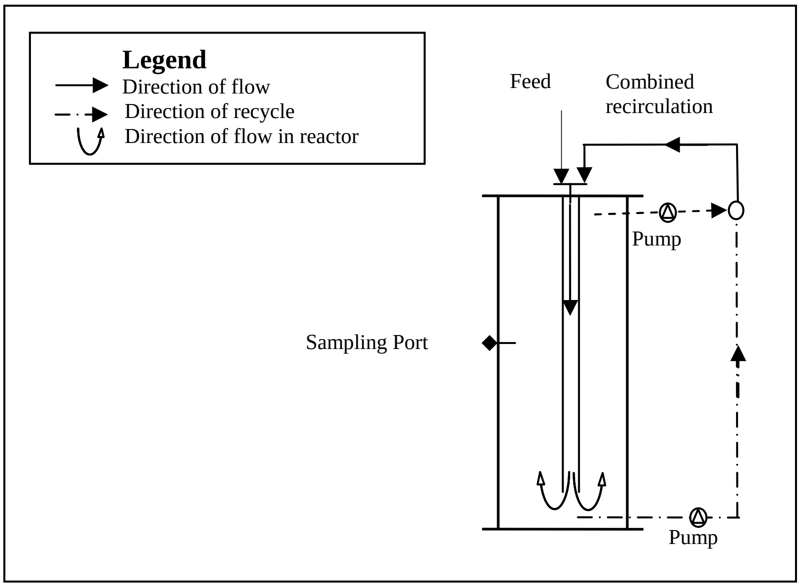

Figure 3.2 Schematic illustration of the Column Upflow Anaerobic Sludge Blanket-type Recycling Sludge Bed Reactor (RSBRc) used in this study.

3.3.1.3 The Continuous Stirred Tank Reactor

The STR (working volume 20 ℓ) was constructed from a 30 cm diameter Perspex cylinder, fitted with a Perspex base-plate and a lid with a single rubber-stoppered inlet port for receiving feed.

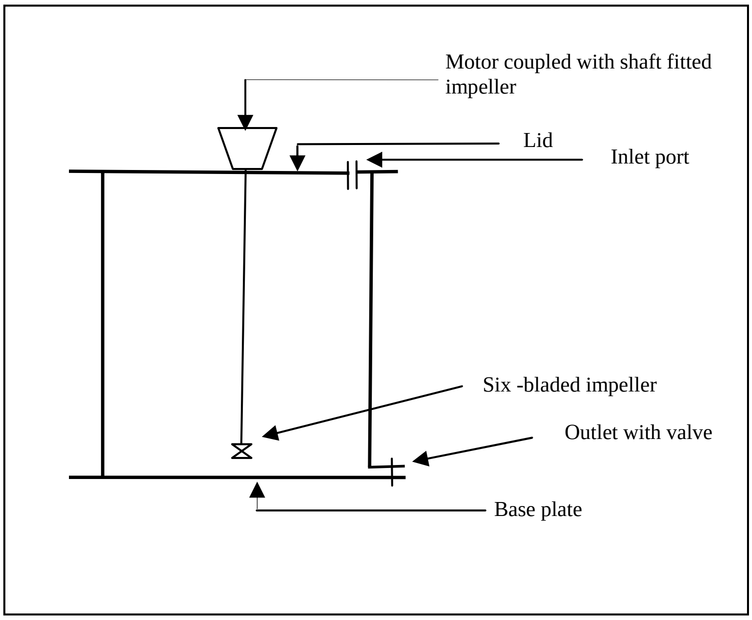

Figure 3.3 Schematic illustration of the Continuous Stirred Tank Reactor (STR) used in this study.

An outlet with a valve was installed at the base of the reactor for drainage purposes. The reactor was sealed to ensure anaerobic conditions and complete mixing was achieved by means of a lid-mounted 0.25 kW speed regulated Bonfigioli motor and gearbox driver with a six-bladed impeller. The impeller was suspended 10 mm from the bottom of the reactor.

3.3.1.4 Operational Protocol

PS was collected from the Grahamstown Disposal Works (GDW), passed through a sieve (50µm mesh pore size) to remove large particles and stored at $4^{o}C$ for a maximum period of 2 weeks. When required, PS was diluted with tap water to obtain a feed with total chemical oxygen demand (CODt) of 4000 mg/ℓ. Sulphate feed of 4000 mg/ℓ was prepared by dissolving Na_2SO_4 (Merck Chemical Pty Ltd) in tap water. On reactor start-up, a mixture comprising equal volumes of the PS and sulphate feeds (ratio 1:1) was prepared and to this was added 20% of active SRP seed sludge harvested from an existing stably operating sulphidogenic bioreactor. The volume of the final mixture was split between the three reactors, RSBRd, RSBRc and the STR. An initial measurement of CODt, soluble COD (CODs), VFA, pH, alkalinity, and sulphide (methods described below) was undertaken at the onset of the experiments.

All three systems were operated under ambient temperature conditions of $\pm 20^{o}C$ for a period of 60 days. No attempt was made to control the pH of the reactors. The linked recycle of overflow and settled sludge in the upflow RSBRs was operated such that a complete volume change in both reactors occurred approximately every 20 hrs. At the end of each seven day period, a uniform sample (15% of volume) was collected for analysis from all three systems. Due to the structure of the RSBRd and RSBRc, with a distinct sludge bed and an upper liquid portion, both systems were physically agitated for three minutes in order to obtain the uniform sample. The sample extracted from each of the three reactors was replaced with an equal volume of feed at the end of each sampling regime. The study focused on the reactor start-up phase where hydrolysis and sulphate reduction may be uncoupled to give a comparative indication of the influence of reactor configuration on hydrolysis.

3.3.2 Analytical Methods

3.3.2.1 Chemical Oxygen Demand

CODt was determined using Merck Spectroquant® test kit # 14541(COD Solution A, #1.14538.0065 and COD Solution B, # 1.14539.0495, Merck KGaA, Germany) according to the manufacturer's instructions. Soluble chemical oxygen demand (CODs) was determined by filtering samples through 0.45 µm cellulose acetate filters (Whatman Int, # 70000002) and measuring the COD of the filtrate. Sulphide, which might contribute to COD, was eliminated prior to analysis by addition of 2 drops of concentrated H_2SO_4 into the samples and shaking for two minutes to allow the release of sulphide gas from the samples.

3.3.2.2 Sulphide

Sulphide was analysed with Merck Spectroquant® test kit, # 1.14779.001 from Merck KGaA, Germany. Absorbance was read with a Merck Spectroquant SQ118.

3.3.2.3 Sulphate

Sulphate was determined by ion chromatography and using Waters Ion Analysis Method # A-102. The analytical system consisted of a Waters 717 Autosampler and a Waters 43 Conductivity Detector, and conditions described in **Table 3.1**. Prior to analysis, samples were filtered through a 0.45µm acetate filter to remove particulates.

Table 3.1 Chromatography conditions for sulphate anion analysis.

Eluent	Borate/Gluconate
Pump	Waters 600 Controller and Pump
Column	IC-Pak™ Anion 4.6x50 mm
Data	Empower software
Flow rate	1.0 mℓ/min
Injection	100 µm/min
Detection	430 Conductivity
Range	500µS
Temperature	On
Polarity	+
Background	375 µS

3.3.2.4 Volatile Fatty Acids and Alkalinity

The total volatile fatty acids concentration (VFA) and carbonate (H_2CO_3) alkalinity were determined by the 5-point titration method described by Moosbrugger *et al.* (1992).

3.3.2.5 pH

pH was measured with a WTW PH330 pH meter.

3.3.2.6 Settleable Solids

Settleable solids were determined according to Standard Methods (APHA, 1998).

3.3.2.7 Enzyme Activity Assay

Carbohydrates and proteins constitute the major organic fractions in complex organic biopolymers found in sewage sludge (Goel *et al.*, 1998), and thus enzyme activity assays in this study were limited to α-glucosidase, β-glucosidase and protease as representative of the hydrolysis process. All enzyme assays were carried out in triplicate and included a control. The control for each enzyme assay consisted of the respective reagents with the terminating solution added before the source of the enzyme to ensure zero enzyme activity. The substrate and buffers were pre-warmed for 30 minutes at 37^{o}C before the addition of the sludge samples. The samples were centrifuged in an Eppendorf Centrifuge 5810R. Absorbance measurements were determined with an Aquamate ThermoSpectronic spectrophotometer using a quartz cell of 10 mm light path. Enzyme activities were determined by measuring the enzymatic conversions of synthetic substrates to products that are quantified spectrophotometrically (Obst, 1985) and are expressed in International Units.mℓ$^{-1}$ (IU/mℓ), where one unit is equal to 1 µmol substrate oxidized.min^{-1}.

3.3.2.8 Determination of α-Glucosidase Activity

The activity of α-glucosidase was determined using a reaction mixture consisting of 1 mℓ 0.1% p-nitrophenyl-α-D-glucopyranoside solution, 2.0 mℓ 0.2 M Tris (hydroxymethyl) aminomethane (tris-HCl) pH 7.4 GR buffer and 1.0 mℓ PS which was incubated at 37°C for 1 hour (Richards *et al.*, 1984; Goel *et al.*, 1998). The reaction was stopped with 2 mℓ 0.2 M NaOH as the terminating solution. The reaction mixture was centrifuged at 2500 g for 10 minutes to separate sludge from the supernatant. The absorbance of the resultant colour change as a result of the release of p-nitro phenol ions was measured at 410 nm. A control sample in which the terminating solution was added prior to the addition of the sludge sample was prepared to eliminate any non-enzyme activity. Glucosidase activity was calculated as µmol p-nitro phenol formed/minute. A standard curve was used to quantify the amount of p-nitrophenol released in the reaction.

3.3.2.9 Determination of β-Glucosidase Activity

β-glucosidase activity was determined by a modification of the above procedure using methylumbelliferyl (MUF)-β-D-glucopyranoside (Sigma-Aldrich, Poole, England) as the substrate (Hattenberger *et al.*, 2001). 1.0 mℓ sludge sample was incubated in 1 mℓ 0.4 M glycine buffer (pH 10.8) with 1.0 mℓ 1.5 mM MUF-β-D-glucopyranoside at 37°C for 10 minutes, after which the reaction was terminated with 2.5 mℓ 95% ice-cold ethanol and centrifuged at 2500 g for 10 minutes. The fluorogenic methylumbelliferone product released was measured at an excitation wave length of 365 nm and an emission wavelength of 455 nm. β-glucosidase activity was calculated as µmol methylumbelliferone released per minute.

3.3.2.10 Determination of Protease Activity

Protease activity was determined using a method of Pin *et al.* (1995), in which azocasein was used as the substrate. A reaction mixture consisting of 1.0 mℓ 1% azocasein, 2 mℓ distilled water and 3 mℓ sludge sample was incubated at 37°C for 30 minutes after which the reaction was terminated with 2.0 mℓ 10% wv ice cold trichloroaetic acid (TCA). The mixture was centrifuged at 3000 g for 10 minutes at room temperature, after which 2 mℓ of supernatant was extracted and 2.0 mℓ 2 M NaOH added. A blank, in which the 3.0 mℓ sludge sample was substituted with 3.0 mℓ distilled water, was prepared, while a single control was prepared for each assay. In the control, TCA was added to the sludge sample at the commencement of the 30 minute incubation period rather than at the end and vortexed well, while the azocasein was added at the end of the incubation period. The precipitated protein was removed and the precipitated TCA-soluble peptides measured at an absorbance of 440 nm. Enzyme activity was defined as one enzyme unit equivalent to one mg azocasein hydrolysed.

3.3.2.11 Statistical Analysis

Statistical analysis of data was performed using descriptive statistics and one-way ANOVA and, where necessary, data was transformed to reduce variability and non-parametric statistical procedures performed to determine significant differences in the performance of the various reactors in terms of sulphate, sulphide, CODt and VFA concentrations; pH, alkalinity and enzyme activities. A 95% degree of confidence was used whereby the level of statistical significance was accepted at $p<0.05$. Statistical analysis was performed using STATISTICA (data analysis software system), for Windows Version 7.1 (StatSoft, Inc. 2005).

3.4 RESULTS AND DISCUSSION

3.4.1 COD Solubilisation

Figure 3.4 compares the concentration of CODt and CODs in the three reactors over the experimental period and indicates that the reactors with recycle generally performed better than the STR in terms of COD solubilisation. It can be observed in **Figure 3.4a** that the RSBRc performed better than both the RSBRd and the STR in terms of CODt solubilisation. The mean residual CODt in the RSBRc over the experimental period was 9749 mg/ℓ, while that in the RSBRd and STR were 10415 mg/ℓ and 11304 mg/ℓ respectively, giving CODt reductions of 56%, 44% and 40% respectively for the RSBRc, RSBRd and STR due to digestion. **Figure 3.4b** further shows that CODs concentration was also higher in the RSBRc, suggesting COD solubilisation was enhanced in the RSBRc while the RSBRd and the STR were comparable. The mean CODs were 176 mg/ℓ, 133 mg/ℓ and 136 mg/ℓ respectively for the RSBRc, RSBRd and the STR over the experimental period. The concentration of CODs in the RSBRc was significantly higher than in the RSBRd (ANOVA, df=2, $p<0.05$) and the STR (ANOVA, df=2, $p<0.05$).

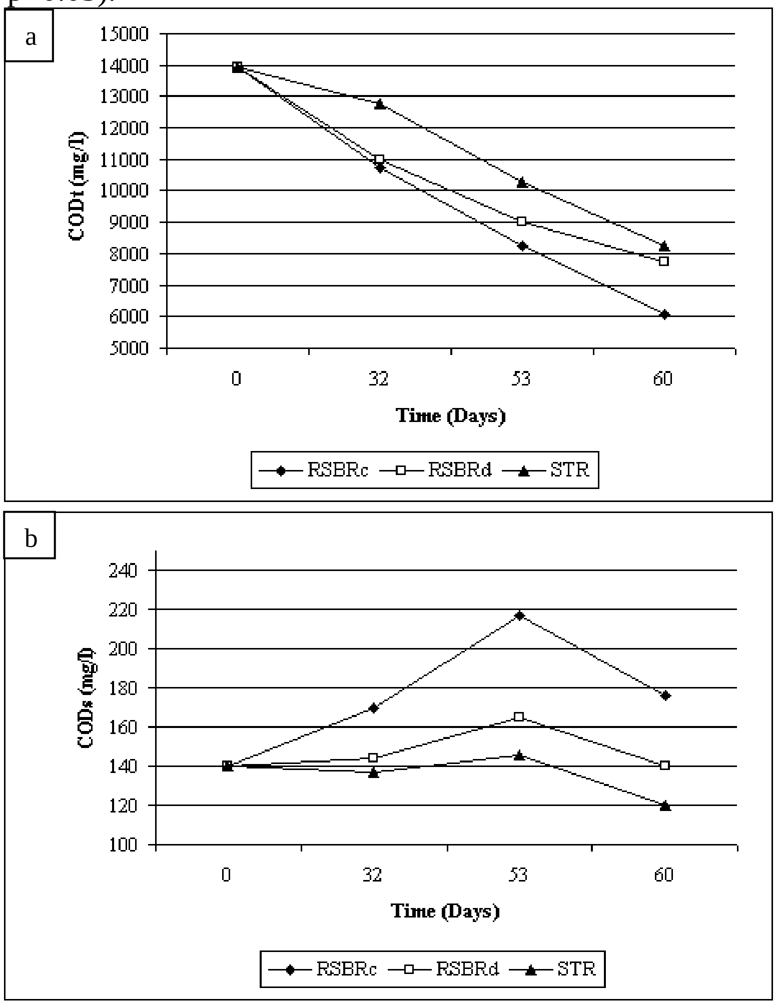

Figure 3.4 Comparative performance of the Dortmund-type Upflow Recycling Sludge Bed Reactor (RSBRd), the Column Upflow Recycling Sludge Bed Reactor (RSBRc) and the Continuous Stirred Tank Reactor (STR) in batch experiments (a) total chemical oxygen demand (CODt) (b) soluble chemical oxygen demand (CODs).

3.4.2 Sulphate Removal and Sulphide Production

Sulphate removal in the reactors is shown in **Figure 3.5**, with just over 22% and 13% sulphate removal recorded for the RSBRc and RSBRd respectively compared to an apparent increase in the STR. The mean sulphate concentration in the RSBRc, the RSBRd and the STR were 1529 mg/ℓ, 1689 mg/ℓ and 1917 mg/ℓ respectively. The mean sulphate removal over the 60 days in the RSBRc was significantly higher than in the RSBRd (ANOVA, df=2, $p<0.05$) and the STR (ANOVA, df=2, $p<0.05$).

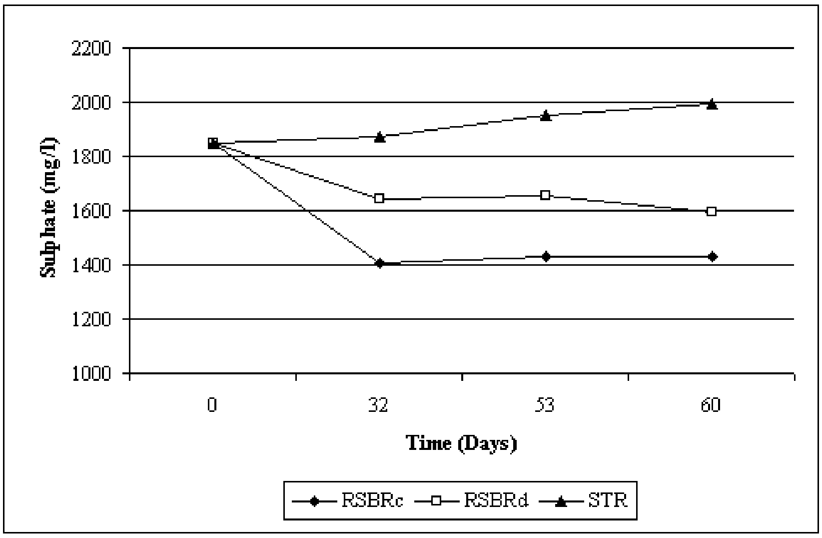

Figure 3.5 Sulphate removals in the Dortmund-type Upflow Recycling Sludge Bed Reactor (RSBRd), the Column Upflow Recycling Sludge Bed Reactor (RSBRc) and the Continuous Stirred Tank Reactor (STR).

3.4.3 Volatile Fatty Acids

VFAs comprise the main intermediary by-products in anaerobic digestion of organic substrates (Ten Brummeler, 1993) and are utilised by SRP in the biological sulphate reduction of AMD (Visser *et al.*, 1993; Finke, 2003). VFA production is shown in **Figure 3.6**.

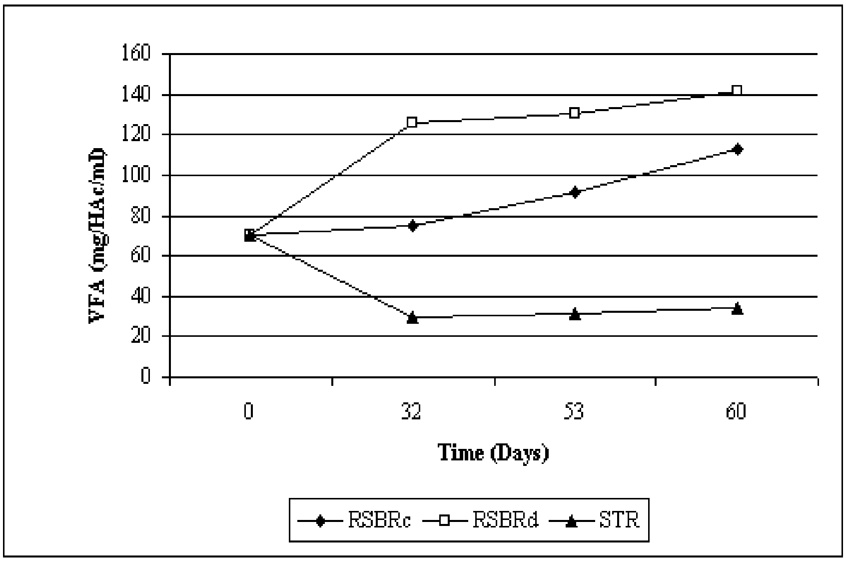

Figure 3.6 Comparison of VFA concentration in the Dortmund-type Upflow Recycling Sludge Bed Reactor (RSBRd), the Column Upflow Recycling Sludge Bed Reactor (RSBRc) and the Continuous Stirred Tank Reactor (STR).

It can be seen that VFA concentration was higher in the reactors with recycle than the STR, with the RSBRd having a higher VFA concentration than the RSBRc. VFA concentration in the RSBRd was significantly higher than in the STR (ANOVA, df=2, $p<0.05$) and that in the RSBRc was also significantly higher than in the STR (ANOVA, df=2, $p<0.05$). The mean VFA concentrations in the reactors were 115 mgHAc/l, 88 mgHAc/l and 41 mgHAc/l in the RSBRd, RSBRc and STR respectively. This represents an increase of 101% and of 60% in VFA concentration in the RSBRd and RSBRc respectively. On the other hand, the STR showed a decrease in VFA concentration of 45% over the experimental period.

3.4.4 pH and Alkalinity

pH and alkalinity are important indicators of the relative activity of SRP populations. Results for the three reactors are shown in **Figure 3.7a** and **b**. These results indicate that all the reactors were operating within the optimal pH range for SRP activity (6.8-7.4) (Yang *et al.*, 1990).

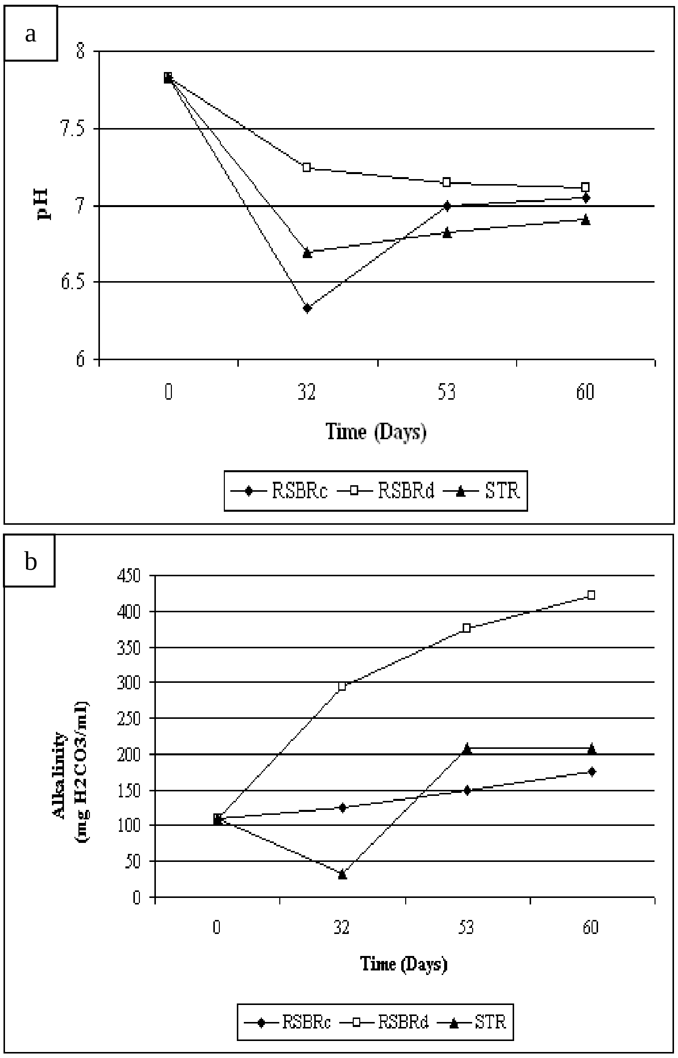

Figure 3.7 Comparison of pH and alkalinity in the Dortmund-type Upflow Recycling Sludge Bed Reactor (RSBRd), the Column Upflow Recycling Sludge Bed Reactor (RSBRc) and the Continuous Stirred Tank Reactor (STR) (a) pH, (b) alkalinity.

Alkalinity production was higher in the RSBRc and the RSBRd than the STR, notwithstanding the RSBRc outliers at day 32. This result would be expected given the elevated sulphate reduction in the former reactors.

3.4.5 Enzyme Activity

Enzymatic activity is an important indicator of particulate organic matter mineralization in wastewater treatment (Goel *et al.*, 1998; Cadoret *et al.*, 2002). An enzyme-based kinetic model (ABK) proposed by South *et al.* (1995) predicts that the rate of hydrolysis for insoluble substrates increases with an increase in enzyme concentration and an increasing amount of available biodegradable adsorption sites i.e. smaller particle sizes and higher content of degradable substrate. Furthermore, enzyme activity has been shown to be in direct proportion to the concentration of enzyme present and with the action of hydrolytic enzyme being independent of the electron acceptor conditions (Goel *et al.*, 1997). An increase in enzyme activity would thus be expected to reflect an increase in hydrolysis rates (Goel *et al.*, 1998). Microoganisms produce and secrete various enzymes that hydrolyse organic matter. Glucosidases are enzymes that play a role in the degradation of starch and the hydrolysis of disaccharides which are obtained from the degradation of polysaccharides. Protease on the other hand, is associated with the cleaving of the peptide bonds in protein molecules (Goel *et al.*, 1998). Furthermore, protein hydrolysis is viewed as the rate limiting step in waste activated sludge digestion (Häner *et al.*, 1994).

The results obtained for the enzyme activity studies are shown in **Figures 3.8.** Enzyme activity was not measured for the reactors at start-up of the experiments due to a breakdown of laboratory equipment and thus the results are not reported. It can be observed from **Figure 3.8a-c** that α -glucosidase and β-glucosidase generally showed higher activities than protease in all the reactors. Enongene (2003) found that carbohydrates constituted the major component of sludge obtained from the GDW. After one month of operation, α-glucosidase activity was slightly higher (14%) in the STR (7 IU/mℓ) than the RSBRd (6 IU/mℓ), but the activity declined in both reactors over the remainder of the experimental period, with the STR generally exhibiting a more pronounced decline in α-glucosidase enzyme activity compared to the RSBRd.

On the other hand, the RSBRc showed the highest α-glucosidase activity of 8 IU/mℓ at day 53, which increased to 11 IU/mℓ by day 60. The STR exhibited the lowest mean α-glucosidase activity over the experimental period. α-Glucosidase activity was significantly higher in the RSBRc than the RSBRd (ANOVA, df=2, $p<0.05$) and the STR (ANOVA, df=2, $p<0.05$). The mean α-glucosidase activity was 6 IU/mℓ, 5 IU/mℓ and 9 IU/mℓ in the RSBRd, the STR and the RSBRc respectively.

β-glucosidase activity was higher (40%) in the STR (9 IU/mℓ) than the RSBRd (6 IU/mℓ) on day 32 but dropped at a much faster rate (40%) in the STR (5 IU/mℓ) compared to 17% in the RSBRc (5 IU/mℓ) through day 53 to day 60. β-glucosidase activity was significantly higher in the RSBRc than in the RSBRd (ANOVA,df=2, $p<0.05$) and the STR (ANOVA, df=2, $p<0.05$) over the experimental period, with mean activities of 5 IU/mℓ, 6 IU and 9 IU/mℓ respectively. The mean β-glucosidase activity was however similar in the STR and the RSBRd over the experimental period. The activity of β-glucosidase may have an effect on the hydrolysis step in PS solubilisation, since it is thought to be the rate-limiting step in cellulose degradation (Alef and Nannipieri, 1995).

Protease activity was 96% higher in the RSBRd at 3 IU/mℓ compared to 0.1 IU/mℓ in the STR on day 32 and, although activity dropped to 0.7 IU/mℓ by day 60 compared to 0.8 IU/mℓ in the STR, the mean protease activity over the experimental period still remained far higher in the RSBRd at 1 IU/mℓ compared to 0.1 IU/mℓ in the STR, an increase in activity of over 87%. The protease activity in the RSBRc remained relatively constant at 0.5 IU/mℓ from day 32 and 0.5 IU/mℓ at the end of the experimental period, registering a mean activity of 0.5 IU/mℓ. Although no significant difference was found in protease activity in all three reactors (ANOVA, p>0.05), the mean protease activity was however highest in the RSBRd at 1 IU/mℓ and least in the STR at 0.1 IU/mℓ over the experimental period.

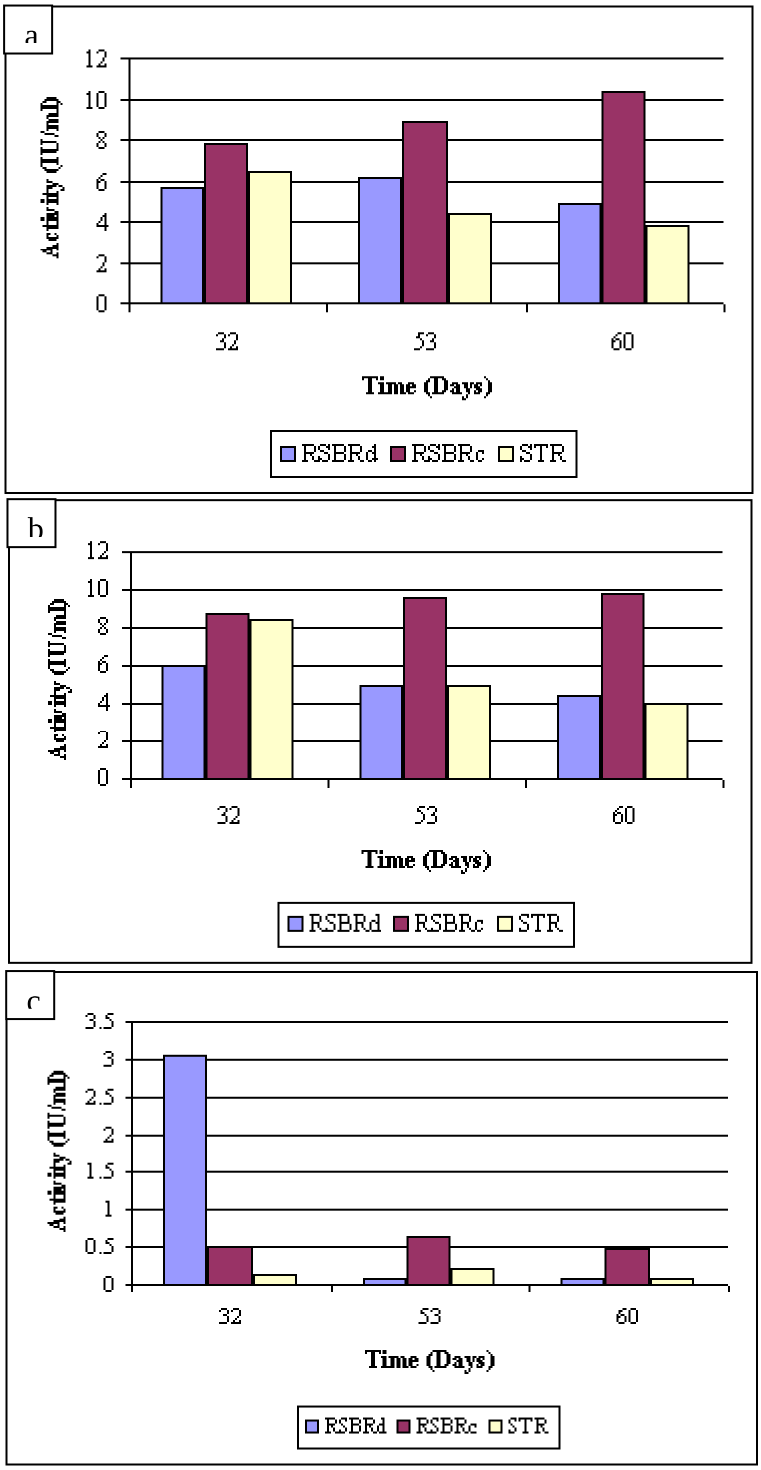

Figure 3.8 Comparison of enzyme activities in the Dortmund-type Upflow Recycling Sludge Bed Reactor (RSBRd), the Column Upflow Recycling Sludge Bed Reactor (RSBRc) and the Continuous Stirred Tank Reactor (STR) (a) α -glucosidase activity (b) β-glucosidase activity (c) protease activity.

It has been reported that the major activity of hydrolytic enzymes is associated with sludge flocs and may be intricately linked within the extra-cellular polymeric substances (EPS) of the sludge floc, with suggestions that the EPS may indeed harbour a large pool of extra cellular enzymes (Frølund *et al.*, 1995; Goel *et al.*, 1998; Guellil *et al.*, 2001). The immobilisation of enzyme activity in flow-through systems, may offer advantages over completely mixed systems as microorganisms need not waste energy in continuously replenishing the enzyme pool (Goel *et al.*, 1998). Furthermore, with a higher operational stability and an easy access to co-enzymes and substrates having been advanced as further advantages of enzyme immobilisation (Phillips and Poon, 1988), the comparatively better performance of the RSBRd and the RSBRc over the STR would seem to support this observation.

3.5 CONCLUSIONS

While there are methodological problems inherent in the rigorous comparison of rates of hydrolysis in different reactor operating regimes, the results reported here nevertheless provide a preliminary indication that hydrolysis may well proceed at different rates within different reactor configuration environments. Enhanced hydrolysis of PS and sulphate reduction have been demonstrated to be feasible in commonly used reactor configurations in sewage treatment. Both the RSBRc and the RSBRd were shown to support enhanced hydrolysis of PS and sulphate reduction. However, taken overall, the RSBRc appeared to perform comparatively better than the RSBRd, while the STR generally showed the worst performance of the three reactors studied. Although the reactors were not operated at extended steady state conditions, the results obtained in this study seem to support previous findings of Whittington-Jones (2000) and Enongene (2003) that hydrolysis was enhanced in an RSBR compared to a STR environment. Based on the scale-up/scale-down process undertaken, the RSBRc was selected as the appropriate reactor design for the hydrolysis unit operation in the next stage of the process development.

4 THE MULTI-STAGE PROCESS CONFIGURATION

4.1 INTRODUCTION

In previous development of the Rhodes BioSURE Process, Whittington-Jones (2000) and Corbett (2001) had found that a dual-stage process in which the hydrolysis of PS and biological sulphate reduction were uncoupled, achieved higher sulphate reduction throughput than a single-stage configuration in which the performance of reactions was averaged. In terms of process development, it was envisaged that enhanced hydrolysis of PS could be optimised effectively in a first reactor and the products thereof fed into the second reactor where sulphate reduction could be independently optimised. What was not clear, however, was whether these advantages in uncoupling hydrolysis from the sulphate reduction process would translate in the large-scale process environment, and in particular, using sewage treatment reactor configurations. A process development study was thus undertaken in order to scale-up the preliminary bench-scale reactor studies and to further investigate the dual-stage process configuration proposal. Due to project time constraints, it was decided that both pilot-scale and technical-scale studies of the dual-stage reactor configuration be undertaken simultaneously. While the choice of the UASB-type RSBR for the pilot-scale was based on the comparative evaluation study reported in Chapter 3, the availability of Dortmund settling tanks on the site at Ancor Works (Springs) where the technical-scale study was to be undertaken indicated that these be used in this study.

4.2 RESEARCH OBJECTIVES

The objectives of the studies reported here were:

1. To establish whether there are quantifiable advantages in separating the hydrolysis of PS from sulphate reduction;
2. To verify if the sulphate reduction step could be optimised in a completely mixed reactor environment such as the STR as had been suggested by Corbett (2001) and the results of Ristow *et al.* (2004);
3. To undertake further development of the Rhodes BioSURE Process at pilot-scale and technical-scale operations.

4.3 MATERIALS AND METHODS

4.3.1 The Pilot-scale Multi-stage Reactor

The pilot-scale multi-stage reactor included the RSBRc, a STR and a clarifier as laid out in **Figures 4.1** and **4.2**. The RSBRc, with a working volume of 2.5 m^3 was constructed from stainless steel (4.5 m high; 0.95 m in diameter), with a 0.2 m^3 steel cone attached to its base. It had an inner column (20 cm diameter; 1.5 m in length), which was extended to 3.5 m for the second and third phases of the study.

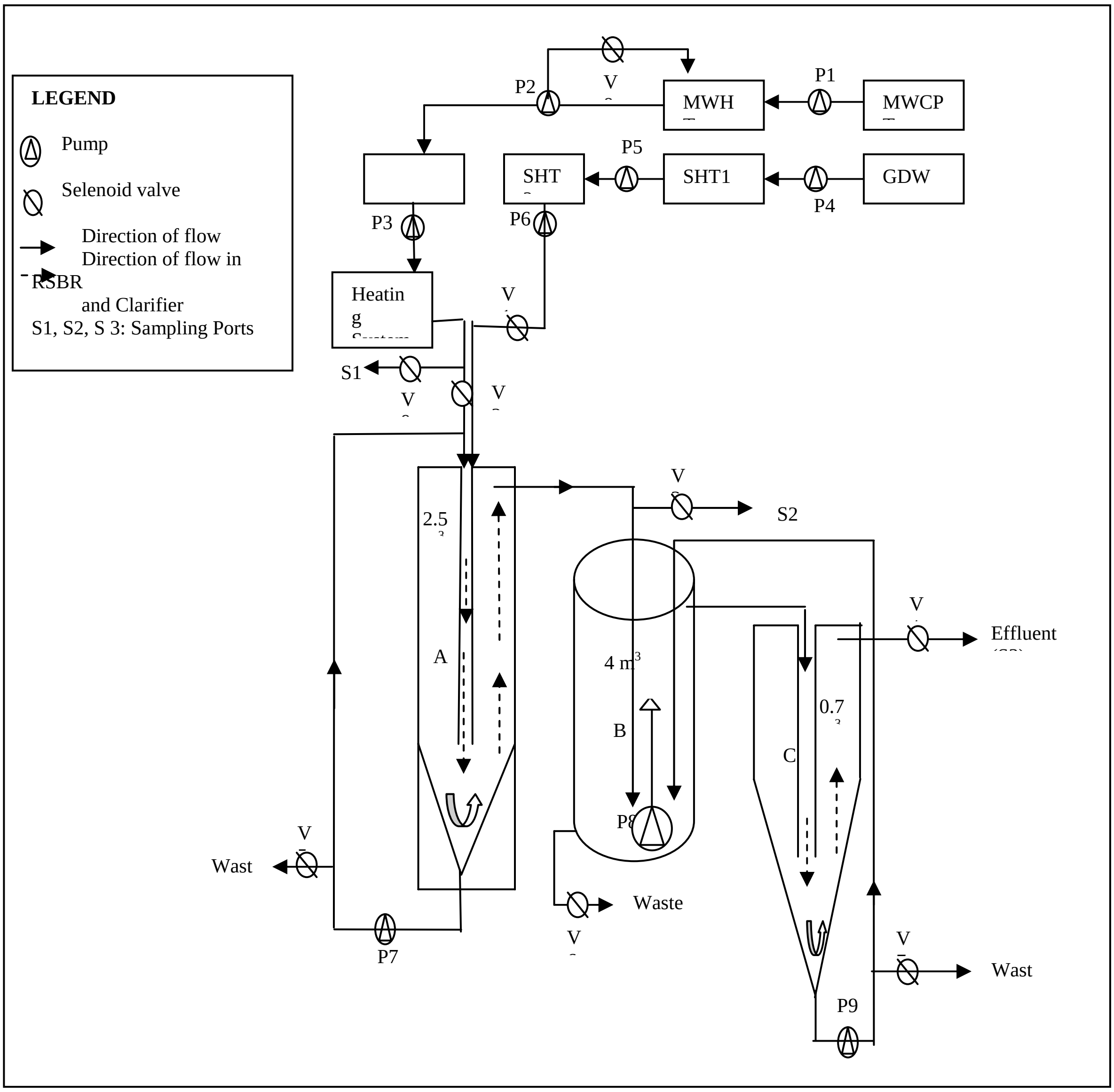

Figure 4.1 Schematic diagram of the Pilot-scale Multi-stage Reactor constructed and operated at the Environmental Biotechnology Research Unit (EBRU), Grahamstown. A= Column Upflow Recycling Sludge Bed Reactor (RSBRc); B= Continuous Stirred Tank Reactor (STR); C= Clarifier; MWCPT= Mine Water Concentrate Preparation Tank; MWHT= Mine Water Holding Tank; MWFT= Mine Water Feed Tank; GDW= Grahamstown Disposal Works; SHT1= Sludge Holding Tank 1; SHT2= Sludge Holding Tank 2.

Figure 4.2 Photograph of the Pilot-scale Multi-stage Reactor at Environmental Biotechnology Research Unit (EBRU), Grahamstown South Africa. 1= Column Upflow Recycling Sludge Bed Reactor (RSBRc); 2= Continuous Stirred Tank Reactor (STR); 3= Clarifier.

Synthetic mine water with a sulphate concentration of 2000 mg/ℓ and devoid of metals was prepared by first dissolving Na_2SO_4 in hot tap water in a 0.75 m^3 calibrated high density polyethylene mine water concentrate preparation tank (MWCPT) to form a sulphate concentrate. This was transferred to a 10 m^3 calibrated high density polyethylene mine water holding tank (MWHT) and diluted with tap water and the total volume brought up to 10 m^3 and thoroughly mixed for 24 hours, after which a portion was transferred to the mine water feed tank (MWFT) from where it was fed into the RSBRc at known flow rates. The mine water was passed through a heat exchange system which maintained the temperature at 25^{o}C and blended with recycled sludge from the cone at the bottom of the RSBRc and fed via a feed port leading directly into the inner column at the top of the reactor. Pre-screened PS was pumped from the underflow lines of the primary clarifiers of the GDW into a high density polyethylene sludge holding tank 1(SHT1) where it was macerated by a grinder for 12 hours to reduce large particles in order to avoid blockages and transferred into a calibrated high density polyethylene sludge holding tank 2(SHT2).

Three experimental phases were investigated and the design parameters are outlined in **Table 4.1**. Depending on a daily determined concentration of the PS in SHT2, a daily loading rate based on the required COD: SO_4 ratio (**Table 4.1**) was calculated and the corresponding PS volume fed manually through the feed port into the RSBRc.

Table 4.1 Pilot-scale Multi-stage Reactor experimental setup parameters for phases 1, 2 and 3 of operation. RSBRc= Column Upflow Recycling Sludge Bed Reactor; STR= Continuous Stirred Tank Reactor.

	Phase 1			**Phase 2**		
Parameter	**RSBRc**	**STR**	**Clarifier**	**RSBRc**	**STR**	**Clarifier**
Volume in m^3	2.5	4.121	0.735	2.5	4.121	0.735
Depth in m	4.5	1.5	1	4.5	1.5	1
Length of inner column in m	1.5	-	-	3.5	-	-
Diameter of Inner column in m	0.2	-	-	0.2	-	-
Seed Mixture in m^3	1.75	2.87		-	-	
Height of Sludge bed in m	4			2.3		
Mine water flow rate in l/hr	60.5	-	-	54.5	-	-
PS flow rate in l/hr	60.5	-	-	54.5	-	-
Combined flow rate l/hr	121	121	121	109	109	109
Re-cycle Rate in l/hr	720	-	-	720	-	-
HRT in hours	20.6	34.1	6.1	22.9	37.8	6.7
$COD:SO_4$ ratio	2:1	-	-	1:1.5	-	-
Period of operation (days)	0-55			56-107		
	Phase 3					
Parameter	**RSBRc**	**STR**	**Clarifier**			
Volume in m^3	2.5	4.121	0.735			
Depth in m	4.5	1.5	1			
Length of inner column in m	3.5	-	-			
Height of Sludge bed in m	2.3					
Diameter of Inner column in m	0.1	-	-			
Seed Mixture in m^3	-	-				
Mine water flow rate in l/hr	54.5	-	-			
PS flow rate in l/hr	54.5	-	-			
Combined flow rate l/hr	109	109	109			
Re-cycle Rate in l/hr	720	-	-			
HRT in hours	22.9	37.8	6.7			
$COD:SO_4$ ratio	1:1	-	-			
Period of Operation (days)	107-177					

The initial seed mixture comprising 70% of the volume of the RSBRc and 70% of the STR volume was used. This mixture was made of 20% SRP sludge which was obtained from the anaerobic digesters of a wastewater treatment plant treating sulphate rich wastewater from a paper and pulp manufacturing process industry, 30% PS and 50% AMD. These were thoroughly mixed by recirculation for 1 month in the RSBRc and complete mixing in the STR in order to encourage the growth of SRP before the commencement of feeding. The overflow from the RSBRc was channeled through a 3 cm diameter polyvinyl chloride (PVC) pipe by gravitational flow into the bottom of the STR. The STR was constructed from an insulated sealed cylindrical plastic tank with a working volume of 4.121 m^3 and was fitted with a submersible pump adapted for complete mixing. The overflow of the STR was gradually introduced into the clarifier by gravitational flow through a 3 cm PVC pipe. The clarifier with a working volume of 0.735 m^3 was constructed from stainless steel and was similar in structure to the RSBR. Sludge was recycled from the bottom of the clarifier back to the STR. The overflow at the top of the clarifier was channeled via a 3 cm diameter PVC pipe to waste.

4.3.2 The Technical-scale Multi-stage Reactor

The technical-scale multi-stage reactor (**Figure 4.3**), which was designed along the same principles as the pilot-scale reactor, was made up of a RSBRd, a STR and a clarifier, all constructed from modified redundant Dortmund settling tanks (**Figure 4.4**) at the ERWAT Ancor Works in Springs, situated about 2.5 km from the Grootvlei Proprietary Gold Mines (Pty) Ltd. The RSBRd was fitted with a recirculation pump that collected settled sludge from the bottom of the tank and blended it with incoming mine water at the feed port. PS was pumped from the primary settling tank of the Ancor Works into a sludge holding tank (SHT) from where, based on daily analysis, required volumes were pumped through an inline Grinder (G), to remove large particles, into the RSBRd. A start-up seed strategy similar to the pilot-scale study was adopted for the technical-scale process. A submersible pump, fitted with high and low level probes, was installed 1 m below the overflow weir of the RSBRd to transfer flow to the STR. The STR was fitted with two submersible pumps. The first pump was modified as a mixer designed to completely agitate the contents of the reactor. The second pump was fitted with a high and a low level probe and performed a similar function to the submersible pump in the RSBRd, transferring the top portion of the liquid contents of the STR into the clarifier at regular intervals. Another pump recycled settled sludge from the bottom of the clarifier back into the STR. The overflow from the clarifier was channeled to an effluent sump from where it was pumped to drain. A single experimental regime was investigated and the design parameters are outlined in **Table 4.2**.

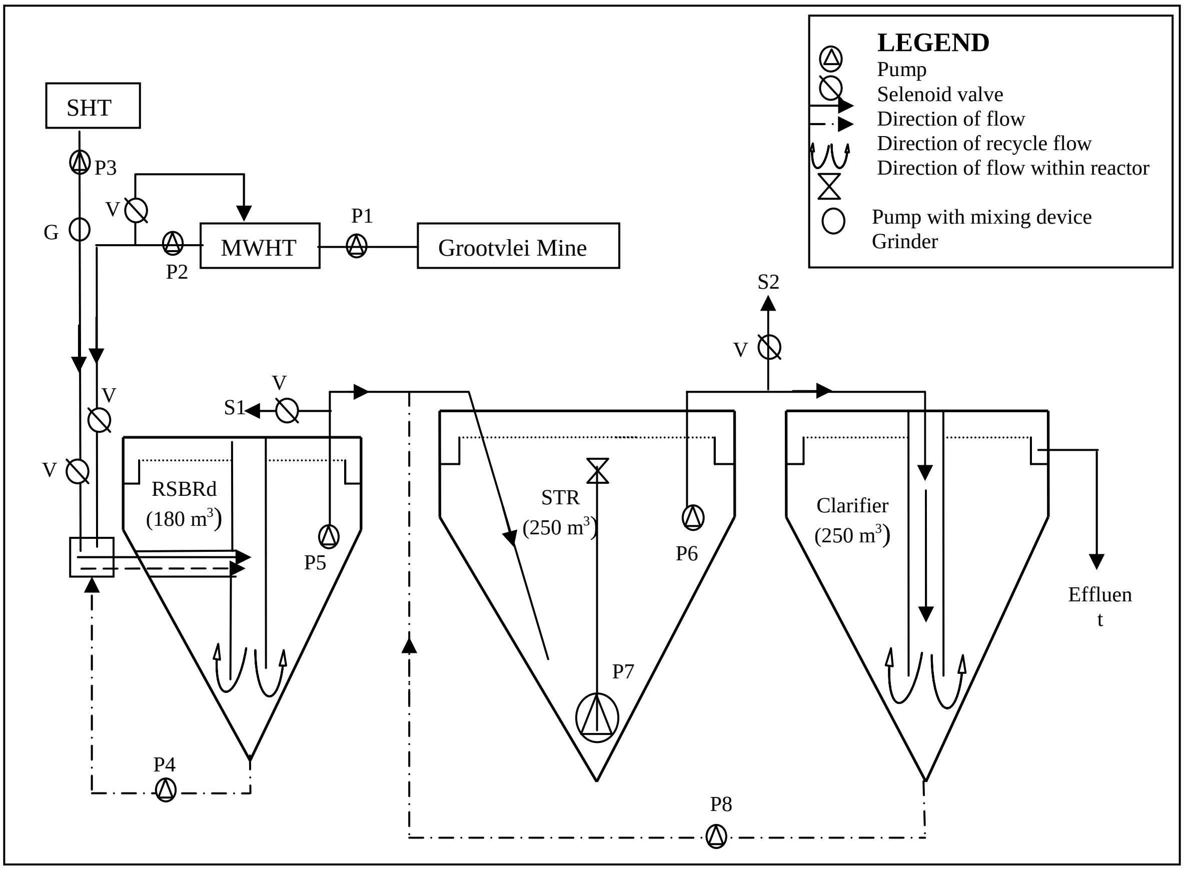

Figure 4.3 Schematic diagram of the Technical-scale Multi-stage Reactor constructed and operated at Ancor Works, Springs. SHT= Sludge holding tank; MWHT= Mine water holding tank; G= Grinder; V= Selenoid valves.

Figure 4.4 Photograph of the Dortmund tanks that were converted into components of the Technical-scale Multi-stage Reactor constructed at Ancor Works, Springs (a) reactor under construction (b) completed reactor sealed to minimise escape of sulphide and to maintain anaerobic conditions. 1= Dortmund-type Upflow Recycling Sludge Bed Reactor (RSBRd); 2= Continuous Stirred Tank Reactor (STR); 3= Clarifier.

Mine water from the Grootlvei Mine, following High Density Sludge Process(HDS) treatment to remove heavy metals, was pumped via a 2.5 km underground pipe line (**Figure 4.5**) to the ERWAT Ancor Works and stored in a 5 Mℓ mine water holding tank (MWHT) from where the appropriate volume was fed continuously to the RSBRd.

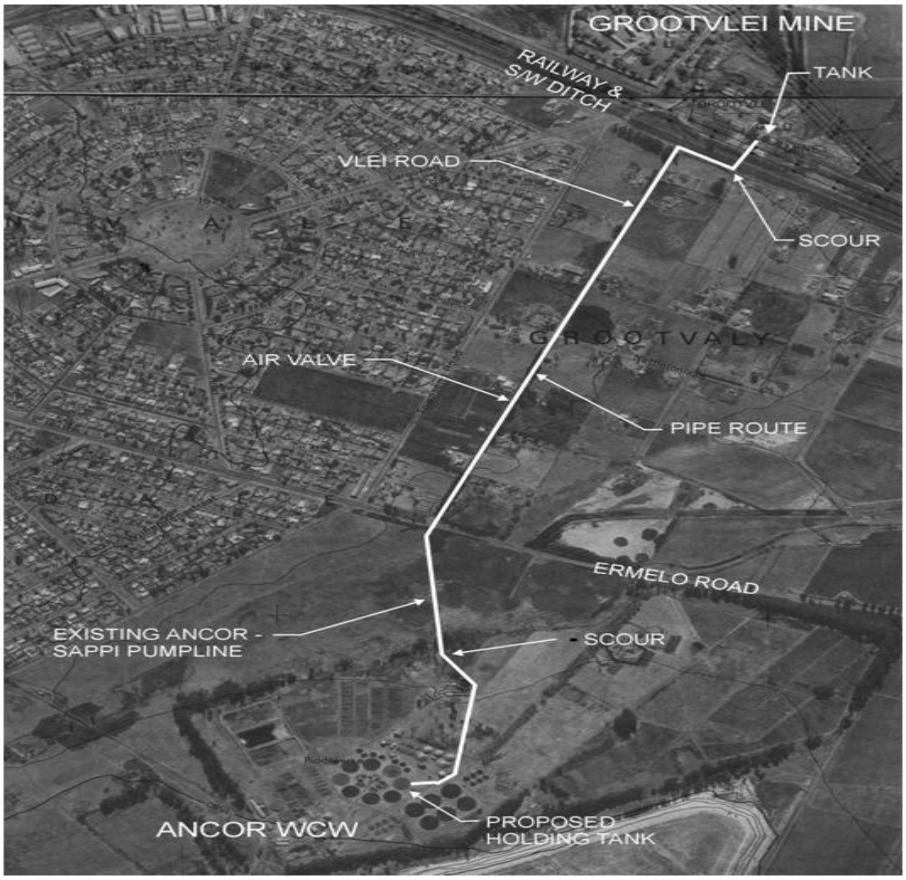

Figure 4.5 Photograph showing pipeline route between Grootvlei Mine and Ancor Works (Springs) through which mine water was supplied to the Technical-scale Multi-stage Reactor.

Table 4.2 Technical-scale Multi-stage Reactor experimental setup parameters. RSBRd= Dortmund-type Upflow Recycling Sludge Bed Reactor; STR= Continuous Stirred Tank Reactor.

	Phase 1		
Parameter	**RSBRd**	**STR**	**Clarifier**
Volume in m^3	180	250	250
Depth in m	9	10	10
Length of inner column in m	8.5	-	-
Diameter of Inner column in m	0.5	-	-
Seed Mixture m^3	126	175	
Mine water flow rate in m^3/hr	2.4	2.4	2.4
PS flow rate in m^3/hr	0.1	0.1	0.1
Combined flow rate l/hr	2.5	2.5	2.5
Re-cycle Rate in m^3/hr	17	-	-
HRT in hours	72	100	100
COD:SO_4 ratio	1:1	-	-

4.3.3 Analytical Methods

4.3.3.1 Chemical Analysis

Chemical oxygen demand, sulphate, sulphide, volatile fatty acids, alkalinity, pH and enzymes activities were determined according to the methods described in Chapter 2.

4.3.3.2 Sulphate Mass Balance

Influent sulphate, effluent sulphate and sulphide concentration, effluent orthosulphate concentration and effluent hydrogen sulphide gas concentrations were measured and converted as ratios of sulphur. The sum of the sulphur equivalents of effluent sulphate, effluent sulphide, orthosulphate and hydrogen sulphide gas were expressed as a percentage of the total sulphur equivalent of influent sulphate.

4.3.3.3 Statistical Analysis

Statistical analysis (ANOVA) was performed using the software package STATISTICA (data analysis software system) Version 7.1 (StatSoft, Inc. 2005, USA).

4.4 RESULTS AND DISCUSSIONS

The start-up strategy utilising 70% reactor volumes of the RSBRc and the STR for seed mixture comprising 20% of seed SRP sludge supplemented with 30% of PS and 50% of AMD adopted for both pilot-scale and technical-scale reactors was designed to encourage the growth of SRP before the commencement of the feed COD: SO_4 ratios.

4.4.1 The Pilot-scale Multi-stage Reactor

4.4.1.1 SO_4 Removal and Sulphide Production

The reactor was operated for 177 days as follows: days 0-55 as a three stage process operation at a COD: SO_4 ratio of 2:1 (phase 1); days 56 -107 as a three stage process operation at COD: SO_4 ratio of 1.5:1 ratio (phase 2) and days 107- 177 as a single-stage process at a COD: SO_4 ratio of 1:1 (phase 3). The actual COD: SO_4 feed ratios measured analytically were 2.1, 1.4 and 0.9 respectively, which were close to the feed as formulated. The purpose of varying the carbon content was to assess the effect of COD: SO_4 ratios on substrate consumption and removal efficiencies. The experiment was completed without desludging the reactor. The performance of the reactor was first evaluated as the full process configuration and secondly as individual unit operations of which the process was composed. Sulphate and sulphide concentrations were monitored as evidence of biological sulphate reduction activity in the pilot-scale reactor. **Table 4.3** shows the average sulphate and sulphide concentrations for feed and effluent while **Figure 4.6** shows the overall trends in sulphate removal, sulphide production and percentage sulphate removal in the pilot-scale process for the first two experimental phases. While frequent process interruptions due to pump failures, pipe blockages, shock loads and changes in feed regimes might have negatively affected process stability and performance, the reactor nonetheless demonstrated a remarkable ability to recover from such perturbations as shown by the sulphate removal trends illustrated in **Figure 4.6a**.

Table 4.3 Mean feed and effluent sulphate, and sulphide concentrations in the Pilot-scale Multi-stage Reactor.

COD:SO_4 Ratio	Sulphate Feed (mg/ℓ)	Sulphate Effluent (mg/ℓ)	Sulphide Effluent (mg/ℓ)
Phase 1(2:1)	1947	608	396
Phase 2 (1.5:1)	2103	931	149
Phase 3 (1:1)	2338	1767	117

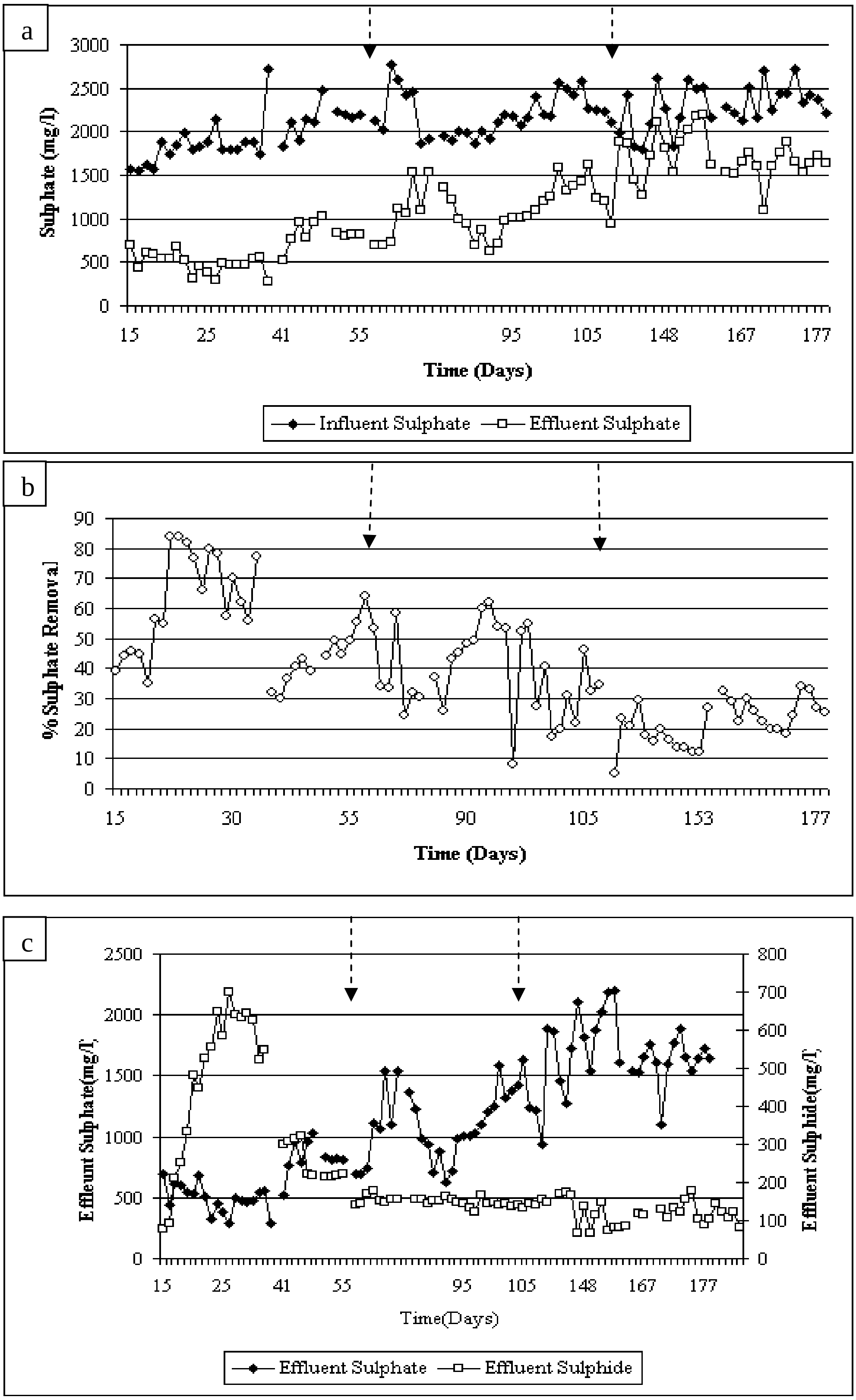

Figure 4.6 Overall performance of the Pilot-scale Multi-stage Reactor (a) Sulphate removal between influent and effluent (b) Percentage sulphate removal between influent and effluent (d) Sulphate removal and sulphide production. Arrows indicate phases 1, 2 and 3 of operation.

The feed and effluent sulphate concentration showed some variation over the experimental period. Sulphate removal rates were not constant throughout the operational period, peaking during phase 1 and gradually declining through phases 2 to 3. The results showed that below a $COD:SO_4$ ratio of 2:1, the system was feed limited. The mean percentage sulphate removal for the reactor was highest during phase 1 (69%), followed by phase 2 (56%) and least during phase 3 (28%), mirroring the gradual decrease in feed $COD:SO_4$ ratios from 2:1, 1.5:1 and 1:1 for phases 1, 2 and 3, respectively. No sulphide was detected in the feed over the experimental period. The mean effluent sulphide concentration generated reflected the mean sulphate removal trend in the three phases of the experiment, with the highest mean concentration of 360 mg/ℓ in phase 1, followed by 149 mg/ℓ in phase 2 and the lowest concentration of 117 mg/ℓ in phase 3.

From **Figure 4.6c** it can be observed that in phase 1, peak sulphate removal recorded during days 20-37 and corresponded with the peak sulphide generation during the same period, after which the performance of the reactors began to decline. Sulphide fluctuated with time, with peak concentrations as high as 600 mg/ℓ detected during this period of operation. Sulphide has been considered to be toxic to both SRP and methanogens (Isa *et al.*, 1986; Reis *et al.*, 1992), with toxicity levels reported at total sulphide concentrations ranging from 50 mg/ℓ to 250 mg/ℓ (Visser *et al.*, 1995). The results of these studies do not appear to corroborate this finding, as high levels of sulphide did not appear to hinder sulphate reduction, and in fact, correlated with the high levels of sulphate removal. Greben *et al.* (2005) showed that higher levels of sulphate reduction occur with increasing sulphide concentrations in biosulphidogenic reactors at various scales of operation.

The reactor experienced a major stoppage at day 35 as a result of pump failure coupled with feed deprivation and non-recirculation during downtime, thus interrupting steady-state operations and causing the initial decline shown in process performance. The switch to a fresh batch of PS feed at start-up after this period might have contributed towards the decline in process performance as the organisms would have had to re-adjust to somewhat new microenvironments or face competition from other organisms. It has been observed that the ratio of organic to sulphate in the feed is a critical determining factor in the relative growth of SRP and MPB, which defines the rate at which sulphate and COD are used (Li *et al.*, 1996). Where sulphate is not limited, the competition is expected to favour the SRP (Colleran *et al.*, 1995). Rinzenma and Lettinga (1988) further observed that the thermodynamics and kinetics of sulphate reduction, methanogenic and acetogenic processes determine the outcome of the competition between these organisms in an anaerobic system.

The sulphate removal and sulphide results are supported by the mean pH values and pH profiles in the pilot-scale reactor as shown in **Table 4.4 and Figure 4.7**, where the mean pH for phase 1 and phase 2 exceeded the optimum pH range (6.8-7.4) for SRP (Yang *et al.*, 1990). According to Visser (1995), SRP may out-compete methanogens at a pH of about 8. The pH values observed in this study would have favoured the SRP over the methanogens.

Table 4.4 Mean pH in the operations of the Pilot-scale Multi-stage Reactor.

	Mean pH	
	Feed	Effluent
Phase 1	6.7	8.1
Phase 2	7.2	7.5
Phase 3	7.3	7.4

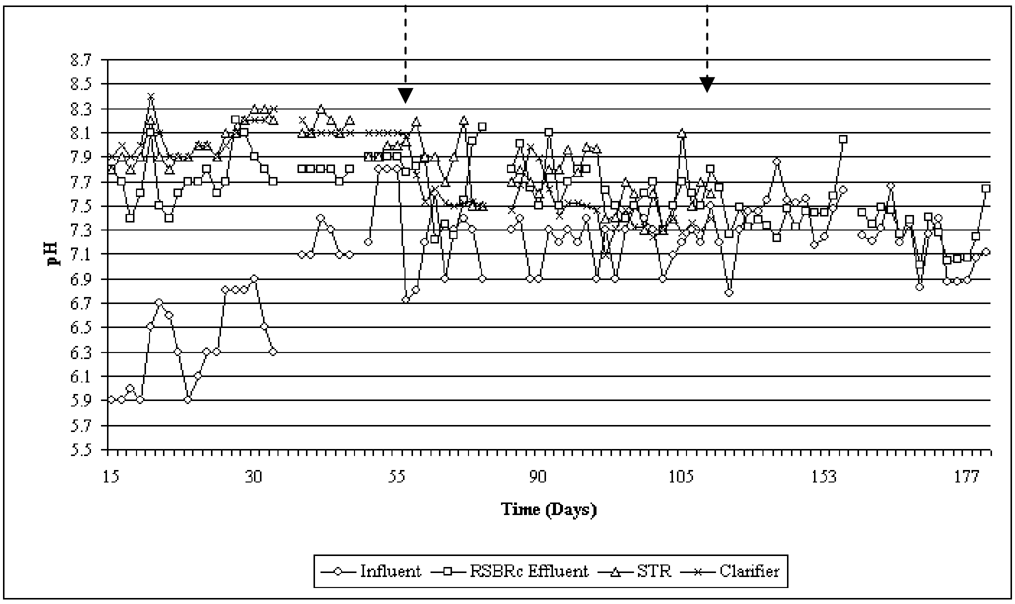

Figure 4.7 pH profiles across the Pilot-scale Multi-stage Reactor. RSBRc= Column Upflow Recycling Sludge Bed Reactor STR= Continuous Stirred Tank Reactor .Arrows indicate phases 1, 2 and 3 of operation.

It should also be noted that sulphate removal decreased with a corresponding decrease in pH from phase 1 to phase 3. In addition, a plot of the effluent sulphate and pH in the RSBRc (**Figure 4.8**) showed a correlation with low effluent sulphate concentrations observed at higher pH. Okabe *et al.* (1992) and Reis *et al.* (1992) contend that an increase of pH above 7 may result in a higher overall sulphate removal rate as a result of reduced toxicity of hydrogen sulphide. Oleskiewicz *et al.* (1989) further stated that the maintenance of a high pH (7.7 to 7.9) favours a tolerance of high concentrations of sulphide.

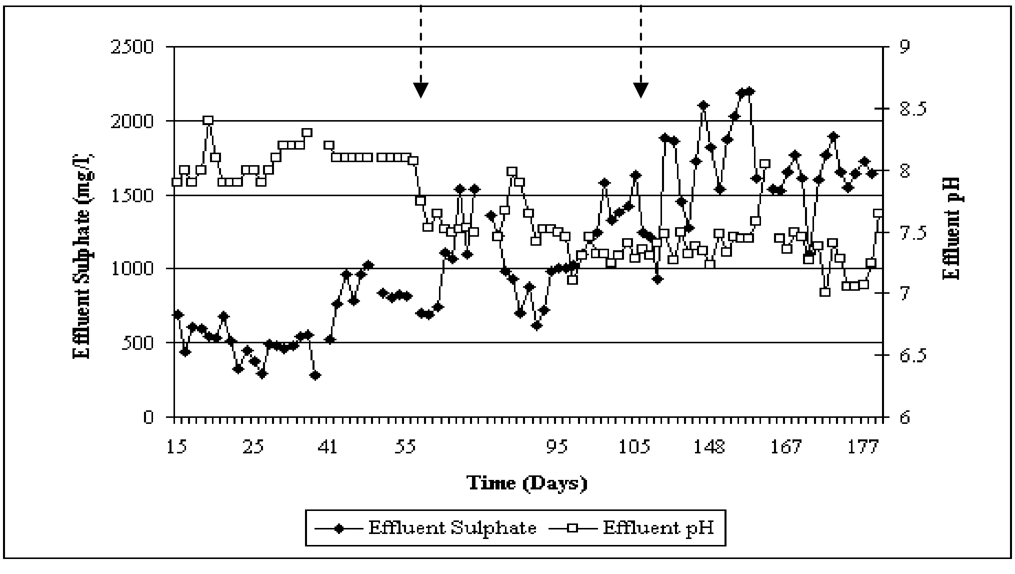

Figure 4.8 Relationship between effluent sulphate and pH in the Pilot-scale Multi-stage Reactor. Arrows indicate phases 1, 2 and 3 of operation.

Towards the end of process steady state, a sulphate mass balance (**Table 4.5**) undertaken during days 165-178 (phase 3) for the RSBRc showed that in the RSBRc, the sulphate that is reduced may exist mainly as elemental sulphur, aqueous sulphide and gaseous sulphide while the unreduced portion remains as residual sulphate in the effluent. Though not operating at steady state as a general decline of process performance had ensued during this period, it was possible nonetheless to achieve a mass balance recovery of 96% in terms of sulphur recovered when all of the above sulphur species were accounted for. It is probable that the sulphate-S that was not accounted for might have been lost during sampling and analysis as gaseous sulphide, or through uptake of sulphur for bacterial growth or due to deposition of sulphur compounds in the reactor.

The RSBRc, STR and clarifier were compared as independent unit operations in terms of sulphate removal efficiency for phases 1 and 2 only as a decision had been taken to decommission the STR and the clarifier at the end of phase 2 based on results outlined below. Each unit operation was evaluated in terms of the feed sulphate and the effluent sulphate. **Table 4.6** shows the mean feed and effluent sulphate and sulphide concentration and mean percentage sulphate removal within the unit operations. In addition, **Figures 4.9** to **4.11** show the sulphate removal, percentage sulphate removal, effluent sulphate and sulphide trends, effluent sulphate and pH trends for the various unit operations.

Table 4.5 Mass balance results indicating percentage sulphur recovery in RSBRc for days 165-177 of phase 3 of the operation of the Pilot-scale Multi-stage Reactor.

	Feed Sulphate				**Effluent Sulphate**						
Day	SO_4(mg/ℓ)	As Mol Fraction	As S^o	Total as Mol Fraction	As SO_4 (mg/ℓ)	As Mol Fraction	As S^o	Mol Frac as S^{2-} (aq)	Mol Frac as S^{2-}(g)	Total as Mol Fraction	% Recovery
165	2283	753.39	-	753.39	1536	506.88	-	183.5	0.21	690.6	91.7
166	2210	729.3	-	729.3	1526	503.58	-	184.5	0.19	688.27	94.4
167	2134	704.22	-	704.22	1655	546.15	-	139.2	0.099	685.45	97.3
168	2515	829.95	2.2	832.15	1765	582.45	51.8	126.8	0.07	761.12	103
169	2170	716.1	4.2	720.3	1610	531.1	19.8	159.8	0.122	710.8	98.7
170	2780	917.4	3.3	920.7	2100	693	15.9	183.5	0.14	734.14	101.2
171	2247	741.51	3.7	745.21	1803	594.99	19.5	127.3	0.05	741.8	99.5
172	2450	808.5	4.3	812.8	1967	649.11	22	134.9	0.112	806.12	99.2
173	2437	804.21	4.7	808.91	1989	656.37	19.4	106.2	0.17	782.14	96.7
174	2720	897.6	3.3	900.9	2050	676.5	25.4	150.5	0.21	852.61	94.6
175	2337	771.21	21.8	793.01	1543	509.19	0.038	178.4	0.199	687.83	86.7
176	2420	798.6	7	805.6	1640	541.2	18.9	214.4	0.18	774.68	100.3
177	2377	784.41	5	789.41	1730	570.9	4.6	124.7	0.09	700.29	88.7
178	2210	729.3	5.6	734.9	1645	542.85	12.7	131.9	0.14	687.59	93.6
									Average		96

It is obvious from these results that on a stand alone basis, the RSBRc outperformed the STR and the clarifier in terms of sulphate removal efficiency (Whittington-Jones, 2000). Sulphate removal was significantly higher in the RSBRc than in the STR during phase 1 (ANOVA, df=2, $p<0.05$) and phase 2 (ANOVA, df=2, $p<0.05$). Sulphate removal was also significantly higher in the RSBRc than in the clarifier during phase 1(ANOVA, df=2, $p<0.05$) and phase 2 (ANOVA, df=2, $p<0.05$) of operation. These findings showed that if optimised, the RSBRc can support sufficiently high rates of sulphate removal on a stand alone basis without recourse to the STR in which maximum sulphate reduction was expected to occur. The RSBRc supported higher mean percentage sulphate removal for both phase 1(55%) and phase 2 (46%), compared to the STR and the clarifier, which achieved a small additional mean percentage sulphate removal.

Table 4.6 Average sulphate feed, and effluent sulphate and sulphide concentrations and mean percentage sulphate removal in individual unit operations in the Pilot-scale Multi-stage Reactor. RSBRc= Column Upflow Recycling Sludge Bed Reactor; STR= Continuous Stirred Tank Reactor.

	Average Sulphate Feed			**Average Sulphate Effluent**		
	RSBRc	STR	Clarifier	RSBRc	STR	Clarifier
Phase 1(2:1)	1947	871	652	871	652	608
Phase 2 (1.5:1)	2104	1145	975	1145	975	931
Phase 3 (1:1)	2338			1767		

	Average Effluent Sulphide		
	RSBRc	STR	Clarifier
Phase 1	371	406	396
Phase 2	73	61	55
Phase 3	30	-	-

	Mean Percentage Sulphate Removal		
	RSBRc	STR	Clarifier
Phase 1	55	25	7
Phase 2	46	15	5
Phase 3	24	-	-

It was, however, noted that during phase 1, sulphate removal in the STR (25%), calculated as removal between influent and effluent from the STR, was comparable to the removal in the RSBRc (24%) during phase 3, though this gradually dropped to 15% during phase 2 of the operation. The clarifier is designed as a sludge recovery and PU and no major sulphate reduction activity was expected to occur in this unit. A 7% sulphate reduction was recorded during phase 1 and 5% during phase 2. These results further confirm the need to re-evaluate the cost advantage of constructing and operating this unit versus the overall performance of the process.

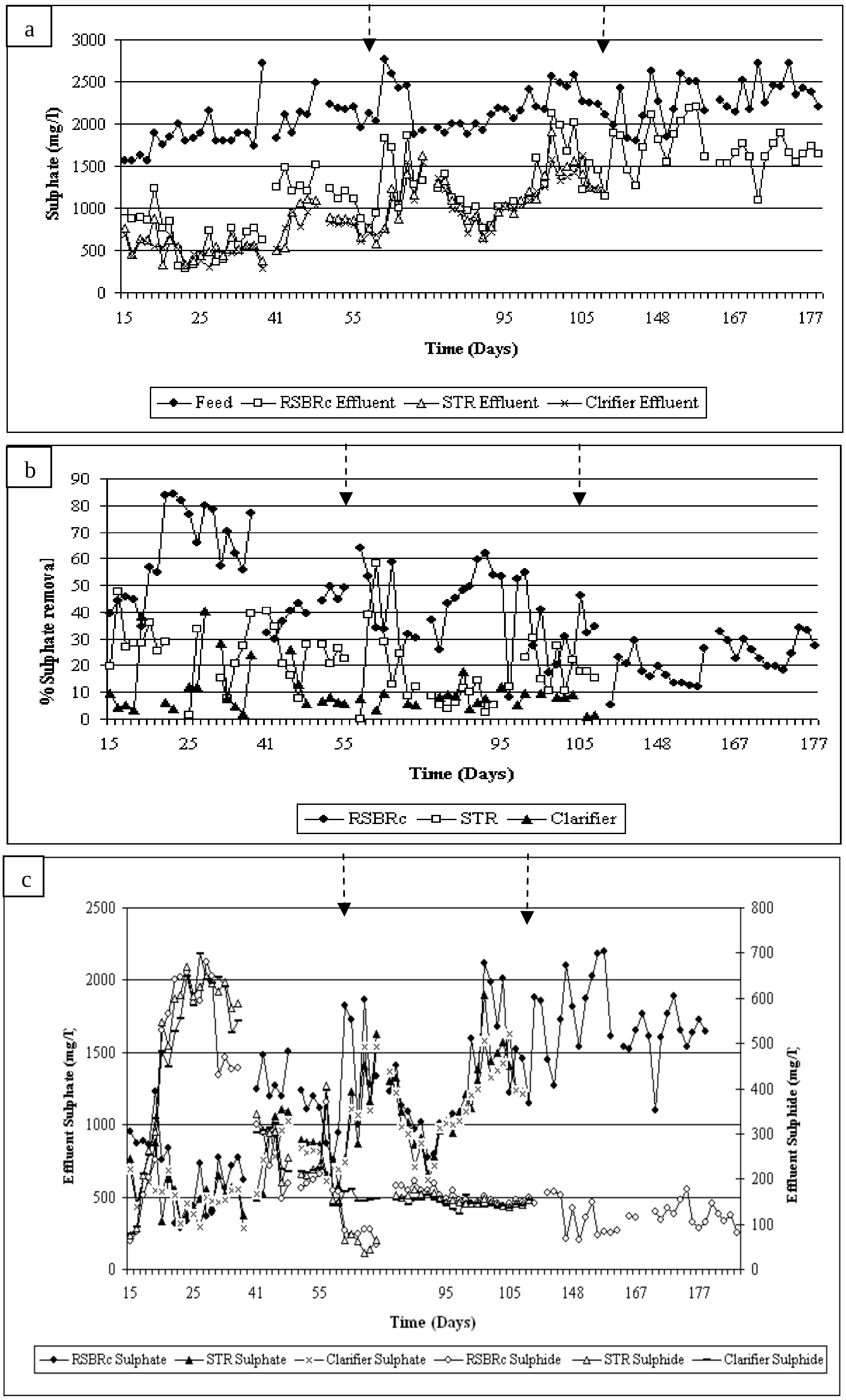

Figure 4.9 Performance of the Pilot-scale Multi-stage Reactor (a) Sulphate removal in the Column Upflow Recycling Sludge Bed Reactor (RSBRc), Continuous Stirred Tank Reactor (STR) and Clarifier (b) Percentage sulphate removal in the Column Upflow Recycling Sludge Bed Reactor (RSBRc), Continuous Stirred Tank Reactor (STR) and Clarifier (c) Sulphate and sulphide in effluent of the Column Upflow Recycling Sludge Bed Reactor (RSBRc), Continuous Stirred Tank Reactor (STR) and Clarifier. Arrows indicate phases 1, 2 and 3 of operation.

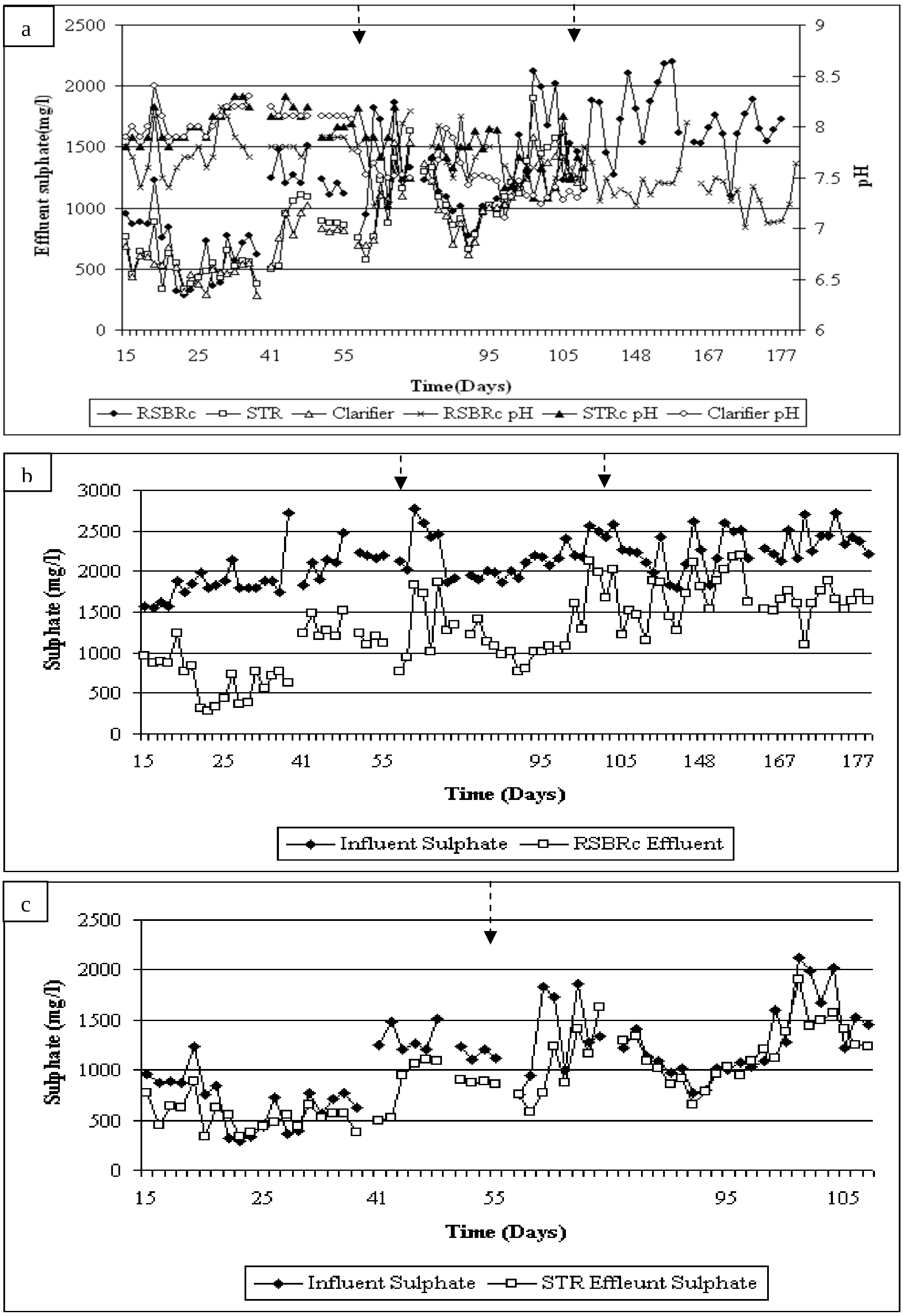

Figure 4.10 Performance of the Pilot-scale Multi-stage Reactor (a) Correlation between sulphate removal and pH in the Column Upflow Recycling Sludge Bed Reactor (RSBRc), Continuous Stirred Tank Reactor (STR) and Clarifier (b) Sulphate removal in Column Upflow Recycling Sludge Bed Reactor (RSBRc) (c) Sulphate removal in Continuous Stirred Tank Reactor (STR). Arrows indicate phases 1, 2 and 3 of operation (a & b) and phases 1 and 2 of operation (c).

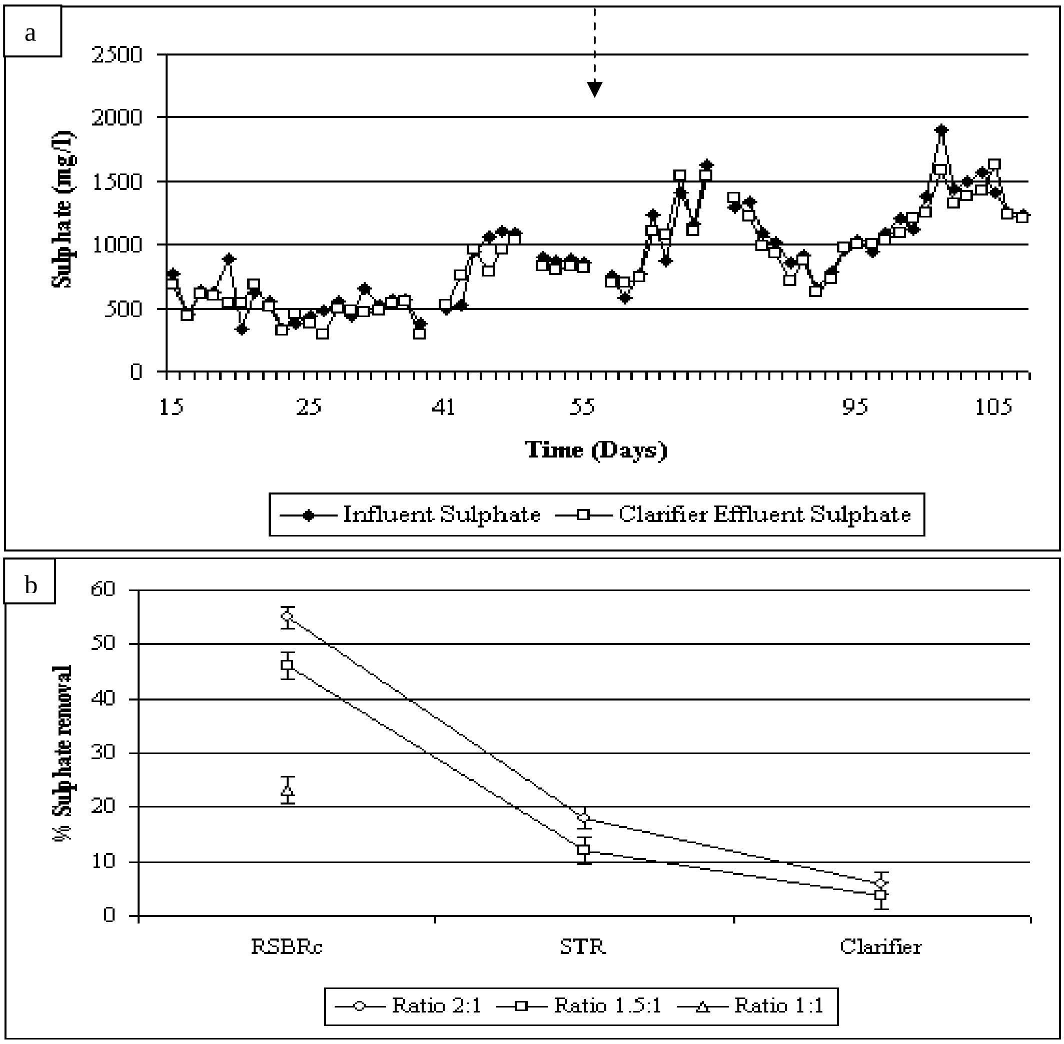

Figure 4.11 Performance of the Pilot-scale Multi-stage Reactor (a) Sulphate removal in Clarifier (b) Mean sulphate removal at COD: SO_4 ratios. Arrows indicate phases 1, 2 of operation.

All three units showed evidence of elevated pH as a result of sulphate reduction (**Table 4.7**), with the STR and clarifier recording slightly higher pH values than the RSBRc for both phases of operation. This might have been attributed to the additional sulphate reduction observed in these units.

Table 4.7 Mean pH in the individual unit operations in the Pilot-scale Multi-stage Reactor. RSBRc= Column Upflow Recycling Sludge Bed Reactor; STR= Continuous Stirred Tank Reactor.

	Mean pH			
	Feed	RSBRc	STR	Clarifier
Phase 1	6.7	7.8	8.1	8.1
Phase 2	7.2	7.6	7.7	7.5
Phase 3	7.3	7.4	-	-

The pH in all unit reactors showed a correlation with effluent sulphate, in the reactors with high sulphate removals, corresponding to high pH values for phase 1 and 2 (**Figure 4.10a**). The mean sulphide concentration recorded was comparable for all three reactors in phases 1 and 2 of operation and was not significantly different (ANOVA, $p>0.05$). It should be noted that the sulphide concentrations detected in the STR and clarifier did not originate entirely from sulphate reduction within these unit operations as the effluent that fed the STR, which in turn fed the clarifier, was sulphide rich effluent from the RSBRc. Therefore any observed increase in sulphide concentration within these two units may be taken to be the result of the small additional sulphate reduction occurring in these unit operations. **Figure 4.11b** shows that sulphate removal increased with an increase in COD: SO_4 feed ratio across the unit reactors. It should be noted in **Figure 4.11b** that the single point represents phase 3 of the operation during which the STR and the clarifier had been decommissioned. The results, which showed higher sulphate removal results at higher COD: SO_4 ratios confirmed results reported by Greben *et al.* (2004), where higher rates of sulphate reduction at higher COD: SO_4 ratios were recorded in reactors fed with acetate and propionate. The 56% mean sulphate removal results obtained for the upflow RSBR is comparable with the 53% result obtained by Enongene (2003) but significantly higher than the 21% recorded by Whittington-Jones (2000) in a laboratory scale downflow RSBR. In addition, a 10% improvement was achieved over the multi-stage laboratory system operated by Whittington-Jones (2000). Previous results (Whittington-Jones, 2000; Corbett, 2001), where an ABR was used in place of the STR as the second stage unit, had suggested that the greater proportion of sulphate reduction occurs in the second stage where the products of hydrolysis (VFAs) generated in the RSRBc were used by SRP for biological sulphate reduction. Given the findings on sustainability in MWTT development reported in Chapter 2, and the decision not to continue with the use of the ABR, it was important to observe that the results derived here showed that sulphate removal may be effectively optimised in a single stage reactor thereby circumventing the additional cost of constructing and operating the STR and clarifier. However, this being the case, a need arises to investigate alternative means of polishing the effluent where a single stage operation is envisaged. This requirement was investigated and is reported in chapter 7.

4.4.1.2 COD Removal in the Pilot-scale Multi-stage Reactor

The average feed and effluent CODt concentrations and mean percentage CODt removal are shown in **Table 4.8** while **Figures 4.12 and 4.13** show the general CODt removal and percentage CODt removal trends. It should be recalled that the RSBRc and the STR were fed a large volume of the start-up sludge mixture as inoculum which explains the high average CODt in the STR effluent feeding the clarifier during phase 1. CODs were monitored only during phase 2 of the operation. Broadly similar trends were observed for CODt removal over the experimental period, except for removal in RSBRc during phase 1. The feed CODt concentrations, measured for phases 1 and 3, showed little variation while the feed CODt for phase 2 was calculated for a 24 hour period and fed once daily. The results showed that the effluent CODt leaving the clarifier at phase 1 was slightly higher than the influent CODt, rendering difficult the estimation of CODt removal and the ratio of $COD_{utilised}$: $SO_{4removed}$ for the reactor as a single unit during phase 1 of the operation. It should also be noted that the clarifier was substantially smaller in capacity (82%) compared to the STR, therefore substantially affecting the settling capacity in the clarifier during phase 1 of the experiment. This would probably have led to an increase in settleable solids (**Figure 4.14**) in the clarifier influent and the corresponding high CODt observed in its effluent.

However, by the end of phase 2, it was observed that the CODt in the effluent of the clarifier had declined substantially, probably as a result of the digestion in the STR, which in turn affected the settling ability of the clarifier. This probably increased the CODt removal in the reactor operating as a unit in phase 2 where approximately 63% COD removal was observed.

Table 4.8 Average feed and effluent total chemical oxygen demand (CODt) concentrations in the Pilot-scale Multi-stage Reactor. RSBRc= Column Upflow Recycling Sludge Bed Reactor; STR= Continuous Stirred Tank Reactor.

	Average CODt Feed (mg/ℓ)			**Average CODt Effluent (mg/ℓ)**		
	RSBRc	STR	Clarifier	RSBRc	STR	Clarifier
Phase 1	4147	2702	10545	2702	10545	4397
Phase 2	3000 (calculated)	955	1412	1412	1412	11109
Phase 3	2182			1601		

	Mean Percentage CODt Removal		
	RSBRc	STR	Clarifier
Phase 1	35	-	58
Phase 2	53	87	21
Phase 3	27		
	Mean Percentage CODt Removal as Single Reactor		
Phase 2	63		
	Residual CODs		
	RSBRc	STR	Clarifier
Phase 2	144	183	192

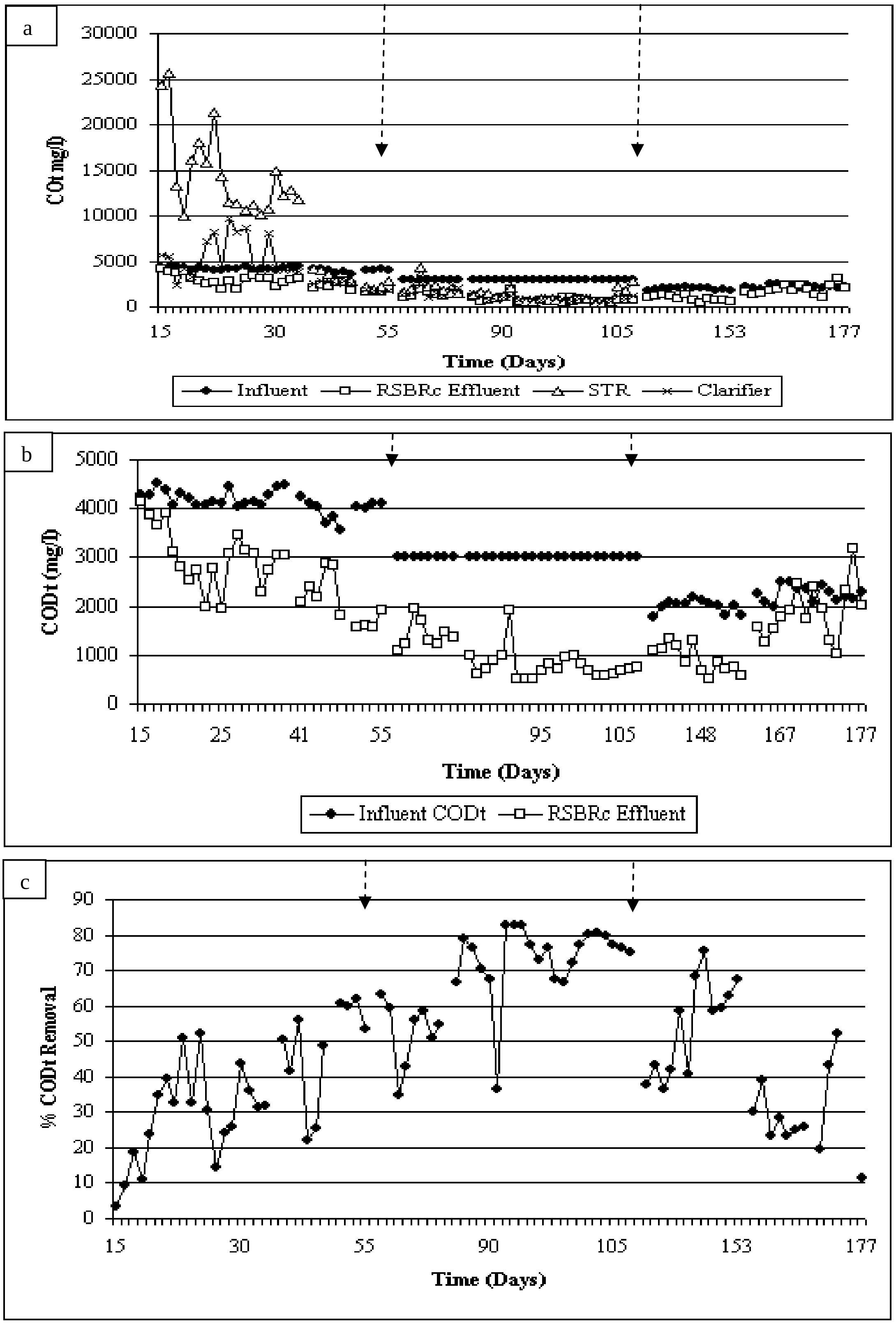

Figure 4.12 Performance of the Pilot-scale Multi-stage Reactor (a) CODt removal in unit operations (b) CODt removal in Column Upflow Recycling Sludge Bed Reactor (RSBRc) (c) Percentage CODt removal in Column Upflow Recycling Sludge Bed Reactor (RSBRc). Arrows indicate phases 1, 2 and 3 of operation.

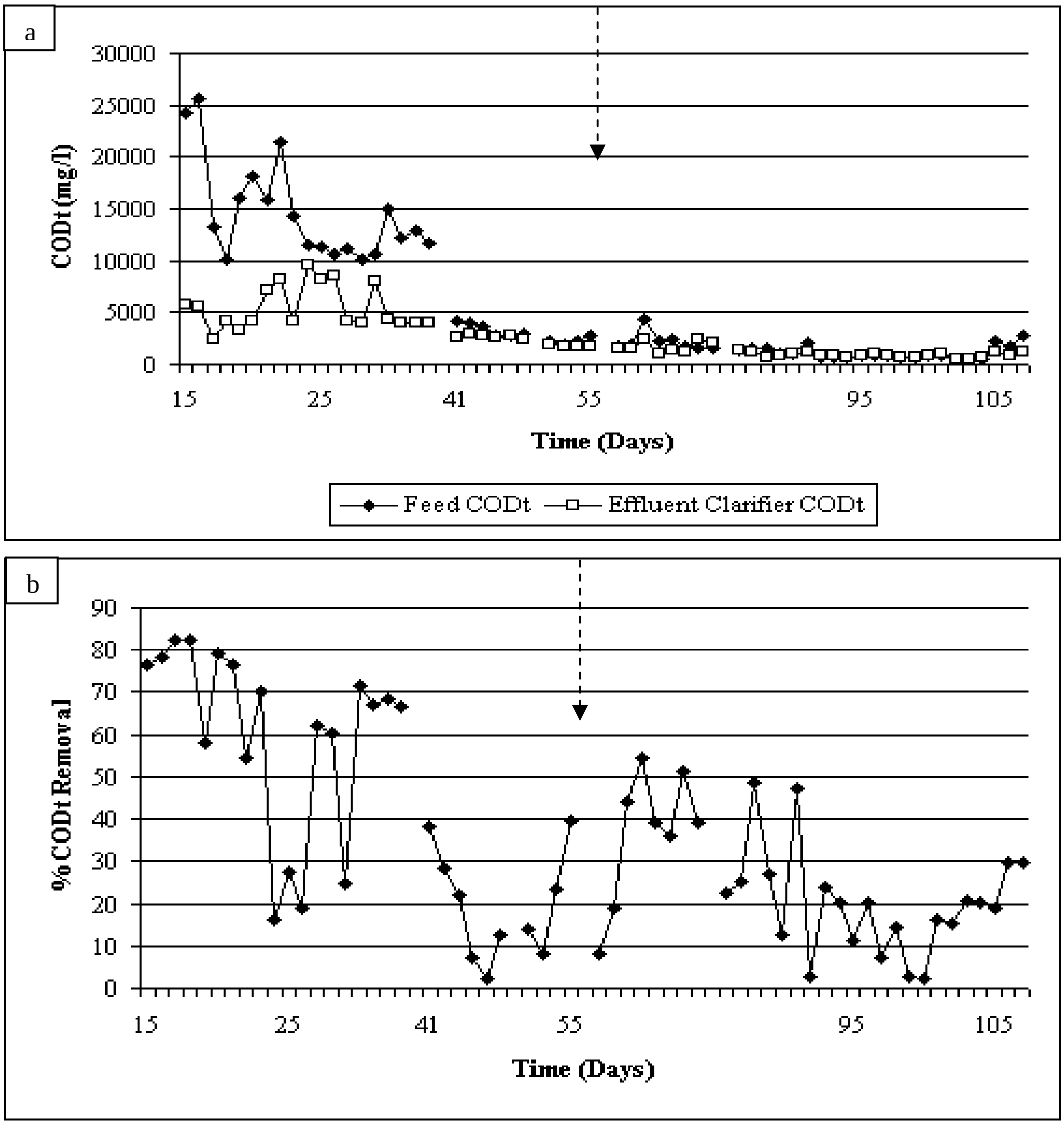

Figure 4.13 Performance of the Pilot-scale Multi-stage Reactor (a) total chemical oxygen demand (CODt) removal in clarifier (b) Percentage total chemical oxygen demand (CODt) removal in clarifier for phase 1 and 2. Arrows indicate phases 1 and 2 of operation.

The average CODt feed in the RSBRc during phase 1 was 4147 mg/ℓ and it can be seen in **Table 4.8** that 35% CODt was removed during this period. This increased to 53% during phase 2 of the experiment and gradually dropped to 27% during phase 3. The general decline in CODt removal during phase 3 corresponds to the decline in SO_4 removal observed during the same period. Although the feed and effluent CODt concentrations were monitored in the STR over the experimental period (**Figure 4.12a**), this was evaluated based on the CODt concentration present at the commencement of the experiment and at the end of the experiment. The results showed that the STR was efficient in sludge digestion, as 87% of the CODt present at the end of phase 1 had been gradually reduced by the end of the phase 2 of the experiment. On the other hand, the results also showed that the clarifier plays a role in CODt removal since at the end of phase 1 the mean average CODt removal was 58%, though this further decreased to 21% at the end of phase 2. This mirrored the decline in the STR during these periods. The residual CODs measured for phase 2 of the experiment also indicated the breakdown of particulate organic matter in the STR and probably the clarifier and suggested that some of the products of hydrolysis were not being utilised for sulphate reduction.

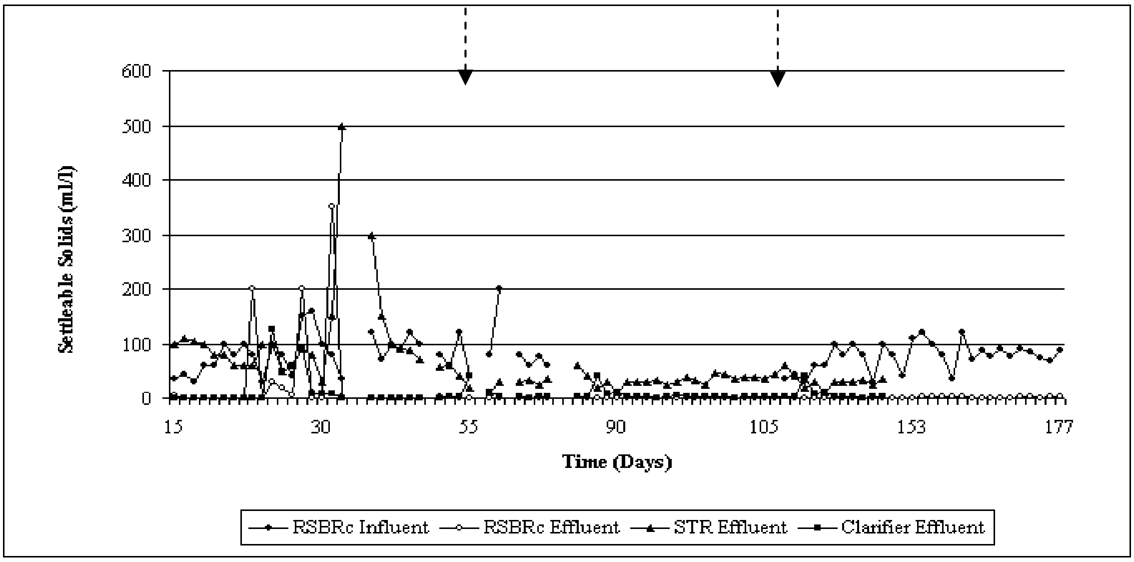

Figure 4.14 Settleable solids in effluent across various unit operations in the Pilot-scale Multi-stage Reactor. RSBRc= Column Upflow Recycling Sludge Bed Reactor; STR= Continuous Stirred Tank Reactor. Arrows indicate phases 1, 2 and 3 of operation.

The effect of the clarifier in removing settleable solids is further demonstrated in **Figure 4.14**. The amount of settleable solids decreased from an average of 68 mℓ/ℓ entering the clarifier from the STR to 6 mℓ/ℓ at the end of phase 2 during which it was measured. These results further showed that the STR and the clarifier could be removed, without negatively affecting the settleable solids removal capacity of the system. The RSBRc was shown to have the potential to remove settleable solids as a stand-alone system, as settleable solids were reduced from 81 mℓ/ℓ to less than 10 mℓ/ℓ over phases 1 and 2 (**Figure 4.14**). It would, however, have to be operated at a slower feed rate and/or with a change in the point of recycle to allow it to operate as a settler as well. In the prevailing conditions of sufficient substrate in the reactors, a rapid growth of hydrolytic and acidogenic bacteria would be anticipated to metabolise the substrate, resulting in more carbon in a form that can be used by SRP and MPB. An increase in the growth of these organisms would lead to a reduction in CODt and hence also, the sulphate levels.

Being a biological system, some degree of inhibition might result leading to a build-up of reduced metabolites, which would lead to a decline in CODt and SO_4 removal. This would be indicated by a corresponding increase in CODt and SO_4 in the effluent, which seemed to have been the case with the reactor towards the end of the experiment, especially since no sludge was wasted over the experimental period. The residual CODs in the effluent of the reactor may suggest that the SRP were no longer able to utilise all the soluble products of hydrolysis.

4.4.2 The Technical-scale Multi-stage Reactor

4.4.2.1 SO_4 Removal and Sulphide Production

The technical-scale multi-stage reactor was operated for a period of 93 days at a COD: SO_4 feed ratio of 1:1. The STR and clarifier were decommissioned as part of the multi-stage process after trends similar to those observed in the pilot-scale were confirmed. The reactor performance was also evaluated as both a complete process and as individual unit operations. Results for the complete technical-scale reactor are presented in **Figure 4.15.**

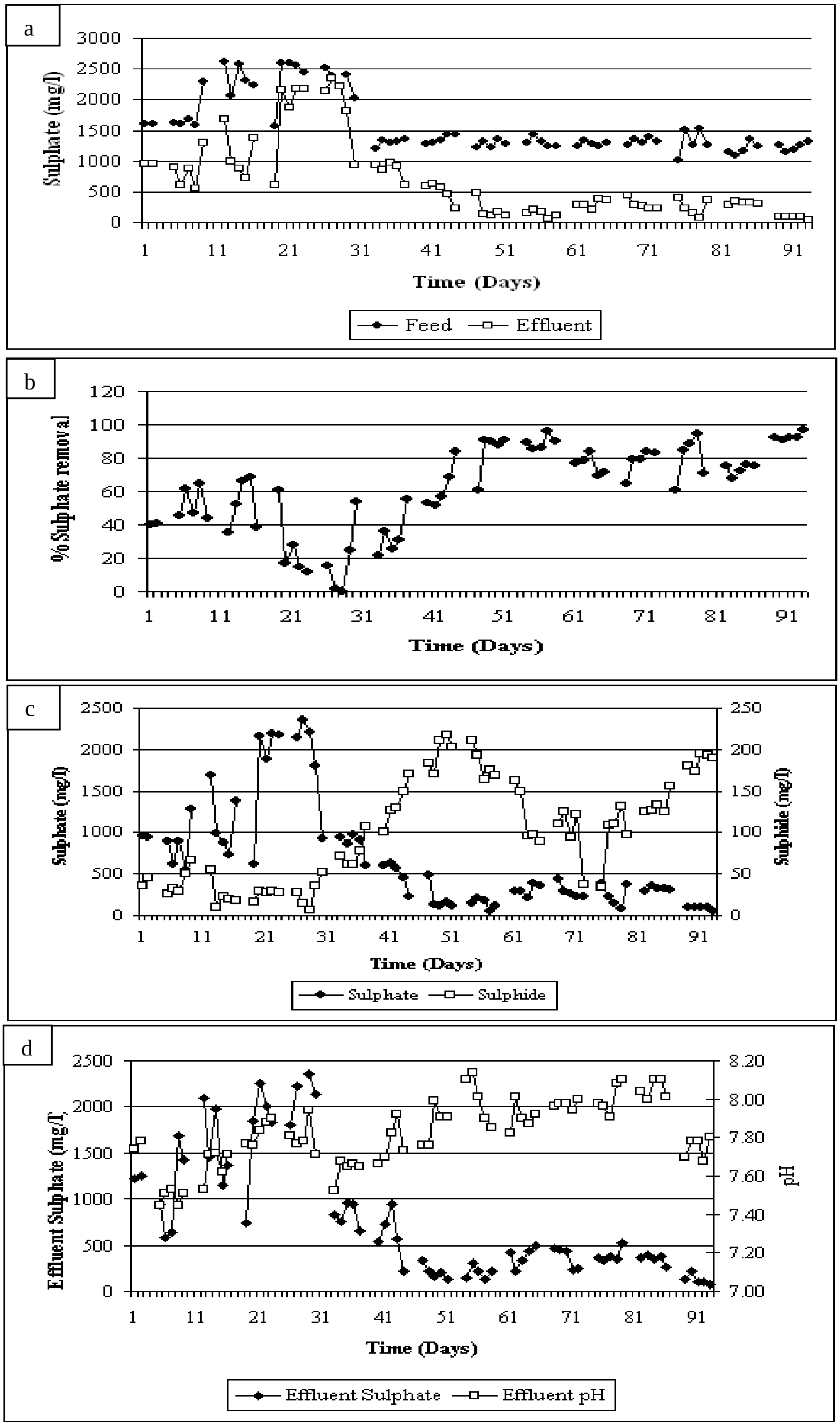

Figure 4.15 Performance of the Technical-scale Multi-stage Reactor as a single unit operation (a) Sulphate removal (b) Percentage sulphate removal (c) Sulphate removal and sulphide generation (d) Effluent sulphate and pH.

The feed and effluent sulphate concentration showed some variation with peak influent values of 2600 mg/ℓ during the initial stages of operation when the reactor was still stabilising with just over 1300 mg/ℓ achieved after day 33. While the average sulphate feed that entered the reactor was 1561 mg/ℓ during the entire period of operation, the average effluent sulphate over the same period was 671 mg/ℓ, representing 57% sulphate removal. However, during steady state operations (day 43-93), average sulphate removal was 82%, with some days recording 96% removal.

The average sulphide produced during this period was 123 mg/ℓ, with peak values of 200 mg/ℓ observed, while the mean pH was 7.9. Although operated as closed systems, a thick coat of elemental sulphur was observed on the surface of the reactor (RSBRd and clarifier) throughout the period of operation and would have accounted for the relatively low amount of sulphide recorded in the effluent. This further suggested that the amount of sulphate removal was probably higher than actually measured. The continuous observation of the coat of elemental sulphur over the experimental period suggested oxygen ingress, leading to the re-oxidation of sulphide and therefore it was impossible for an accurate sulphur mass balance estimation to be carried under these circumstances.

The individual unit operations showed similar trends to results recorded for the pilot-scale reactor. The results for the technical-scale reactor integrating the individual unit operations are shown in **Figure 4.16** and **Figure 4.17.** It can be seen that the rate of sulphate reduction in the RSBRd started off slower than in the STR and the clarifier, but as the reactor stabilised, the rates became comparable, with the RSBRd recording above 80% sulphate removal around day 90. By day 71, it can be observed that the majority of sulphate removal was occurring in the RSBRd, supporting the similar findings observed in the pilot-scale operation.

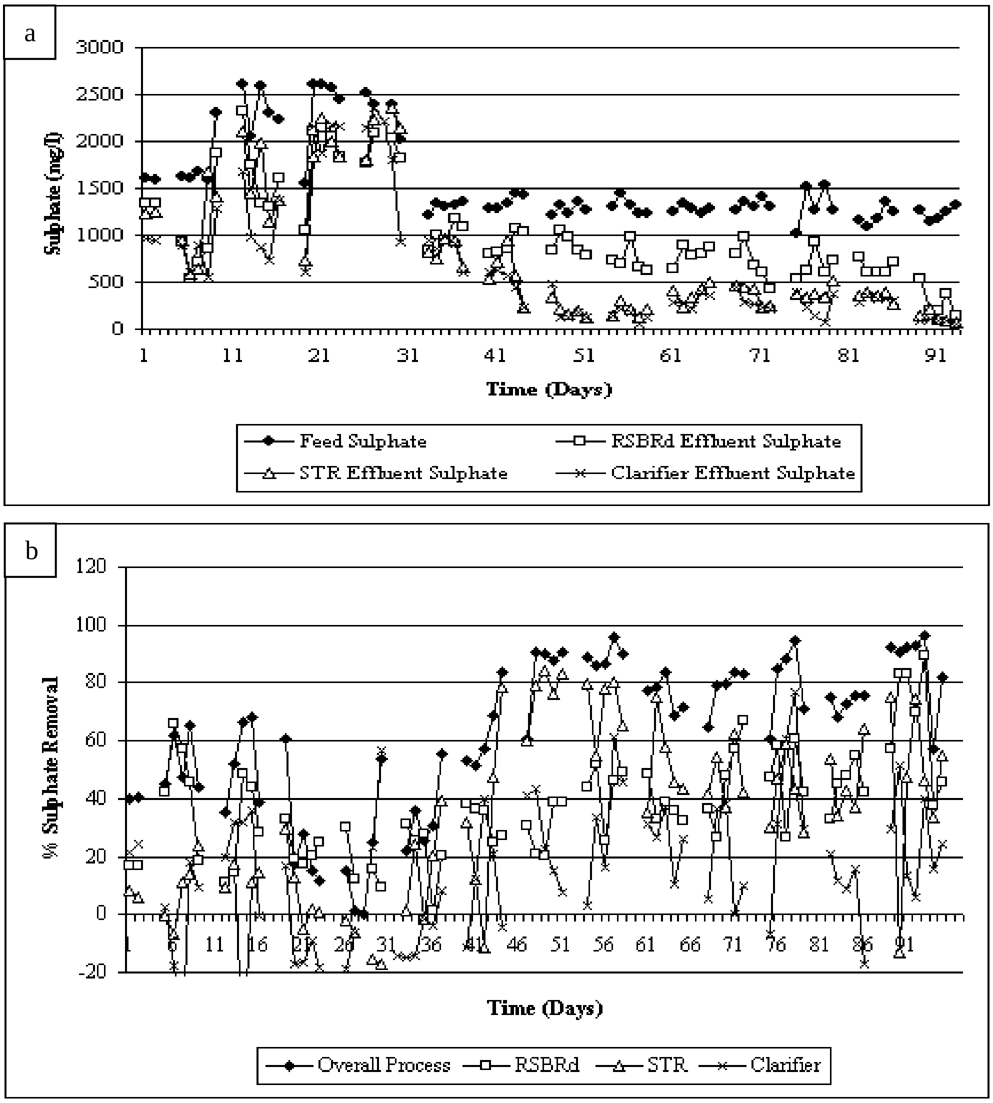

Figure 4.16 Performance of unit operations in the Technical-scale Multi-stage Reactor (a) Sulphate removal across Dortmund-type Upflow Recycling Sludge Bed Reactor (RSBRd), Continuous Stirred Tank Reactor (STR) and Clarifier. (b) Percentage sulphate removal across Dortmund-type Upflow Recycling Sludge Bed Reactor (RSBRd); Continuous Stirred Tank Reactor (STR) and Clarifier.

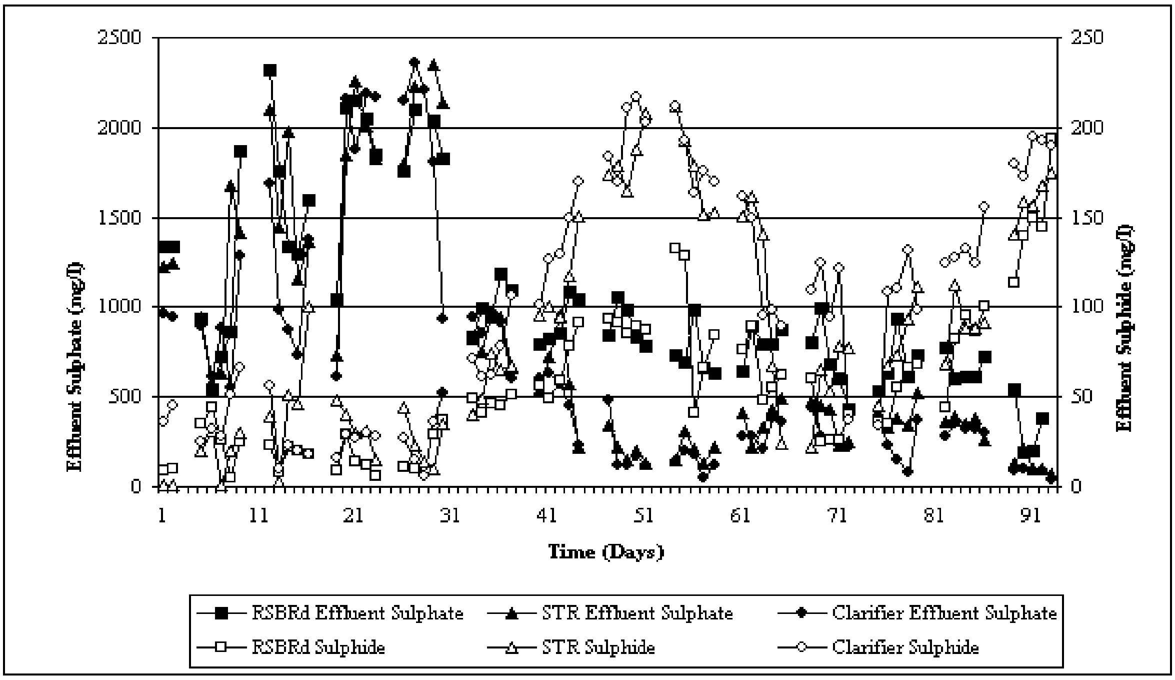

Figure 4.17 Sulphate removal and sulphide generation in the Technical-scale Multi-stage Reactor. RSBRd= Dortmund-type Upflow Recycling Sludge Bed Reactor; STR= Continuous Stirred Tank Reactor.

The mean percentage sulphate reduction, mean sulphide production and mean pH for days 1-93 and 43-93 for the unit operations are shown in **Table 4.9**. Once again, the high pH values for all the unit operations are above optimal for SRP activity. From **Table 4.9**, it can be observed that mean percentage sulphate removal in the STR increased to 58% from 24% during the period day 43-93.

Table 4.9 Mean feed sulphate, effluent sulphate, effluent sulphide, pH and percentage sulphate removal in unit operations of the Technical-scale Multi-stage Reactor. RSBRd= Dortmund-type Upflow Recycling Sludge Bed Reactor; STR= Continuous Stirred Tank Reactor.

	Average Sulphate Feed			**Effluent Sulphate**			**Effluent Sulphide**			**Average pH**		
Period	RSBRd	STR	Clarifier	RSBRd	STR	Clarifier	RSBRd	STR	Clarifier	RSBRd	STR	Clarifier
1-93	1561	1005	761	1005	761	671	58	86	101	8	8	8
43-93	1288	703	295	703	295	233	81	123	145	9	8	8
	Mean Percentage Sulphate as a Unit			**Mean Percentage sulphate Removal in Unit Reactors**								
				RSBRd	STR	Clarifier						
1-93	57			36	24	12						
43-93	82			45	58	21						

An increase of about 75% in mean percentage sulphate reduction was also observed for the clarifier during this period. Although the reactor was operating under steady state conditions during this period, these increments would probably have been as a consequence of augmenting the sludge within the STR on day 61. The fact that improved sulphate removal was observed and considering that sufficient levels of CODs had been prevalent in all the unit operations prior to the augmentation, would suggest that the CODs in the system was in a form that was not readily usable by the SRP. Whittington-Jones (2000) found that approximately 45% of the CODs in the effluent of the RSBRd was not utilised by the microbial consortium in flask experiments designed to test the biodegradability of residual sludge from the RSBRd. This finding also seemed to be in some agreement with results reported by Ristow *et al.* (2004) which showed that approximately 33% of CODt was unbiodegradable and therefore not available for SRP activity.

4.4.2.2 COD Removal in Technical-scale Multi-stage Reactor

The average influent and effluent CODt and percentage CODt removal results are shown in **Table 4.10**. From the commencement of the COD:SO_4 feed at the beginning of the experiment, it was observed that high levels of CODs were present in the RSBRd and the STR, probably as a result of digestion of the seed particulate matter in the reactors at start up. This declined and remained relatively constant until around day 61 when the STR was augmented with sludge, with a resultant increase in the CODs concentration.

Table 4.10 Influent and effluent COD in the Technical-scale Multi-stage Reactor. RSBRd= Dortmund-type Upflow Recycling Sludge Bed Reactor; STR= Continuous Stirred Tank Reactor.

	Influent (mg/ℓ) (Calculated)	**Effluent CODt (mg/ℓ)**			**Effluent CODs (mg/ℓ)**		
Period		RSBRd	CSTR	Clarifier	RSBR	STR	Clarifier
1-93	3327	2542	14179	2106	1287	1488	1355
43-93	3349	2718	22, 968	2437	1677	1907	1836

	Mean Percentage CODt Removal	
Period	**As a unit**	**RSBRd**
1-93	59	24
43-93	45	19

The mean CODs leaving the RSBRd for days 1-93 and 43-93 were 1287 mg/ℓ and 1677 mg/ℓ respectively. For the STR, these were 1483 mg/ℓ and 1907 mg/ℓ, and 1355 mg/ℓ and 1836 mg/ℓ for the clarifier respectively. At a stoichiometric requirement of 2 g COD to reduce 1 g SO_4
(Isa *et al.*, 1986; Lens *et al.*, 1995a), the average 890 mg/ℓ and 1055 mg/ℓ sulphate removed during period 1-93 and 43-93 respectively would have required 1780 mg/ℓ and 2110 mg/ℓ CODs respectively. Considering that the COD:SO_4 feed ratio and the amount of sulphate removal recorded in this study, the effluent CODt and the residual CODs concentrations were highly elevated. This could be attributed to a number of factors. Firstly, the start-up strategy might have overloaded the systems with organic particulate matter and coupled with the subsequent long residence time over the experimental period, one would expect a high degree of solubilisation resulting in the high concentration of the CODs in the system. Secondly, the influent composition, including the type of COD may also be a factor (Polrasert and Hass, 1995). In addition to treating municipal wastewater, the Ancor Works treats substantial liquid waste streams from a number of industries in the Springs area. The presence of any compounds in the PS that are not completely oxidised in the COD method used in this study could have translated into the actual organic carbon in the influent CODt and in the start-up mixture being substantially underestimated. Derycke *et al.* (1993) found that betaine was incompletely oxidized in standard COD assays and accounted for an additional 35% COD compared to that determined analytically. Furthermore, the high amount of residual CODt in the effluent could also have been as a result of minimal sedimentation as the recirculation rate was kept sufficiently high (17 m^3/hr). This was necessitated by two factors. It was not possible to down throttle the recirculation pump to adjust the recirculation speed which would have increased the rate of settling of suspended particulate matter in the reactor. Even when a smaller capacity pump was used, it was impossible to sustain any degree of recirculation in the RSBR and from the clarifier to the STR, due to ongoing blockages, and it was thus resolved to maintain the recirculation at the speed which was sustainable. In addition, the

effluent from the reactors was observed to contain large amounts of floating debris and this might also have contributed to the high residual CODt observed in the effluent. This also raised the question of the quality of the treated effluent for downstream beneficiation processes and suggested some form of remedial action in order to improve the quality of the final effluent.

Choi and Rim (1991) observed that under carbon non-limiting conditions, MPB are able to grow in a non-competitive mode. Furthermore, the carbon might have been in a form not utilisable by the SRP. An inability to efficiently remove acetate has been noted as a problem in certain sulphate reducing systems. Omil *et al.* (1996), Nedwell and Reynolds (1996) and Lens *et al.* (1998) found that this fatty acid generally accounts for the majority of the residual CODs in the effluents of sulphate reducing systems. Since acetate utilising SRP have a relatively poor affinity for sulphate, it is expected that in the presence of substantial amounts of soluble products of hydrolysis such as the residual soluble COD found in the above studies, hydrogen utilising SRP would out compete the acetate utilising SRP (Hulshof Pol *et al.*, 1998), probably resulting in the decline of the sulphate removal efficiency of the system. This would probably explain the decline with time in performance in sulphate removal observed in the pilot-scale reactor.

4.4.3 Comparison of Pilot-scale and Technical-Scale Multi-stage Reactor Results

The COD: SO_4 utilisation ratios used for the pilot-scale and technical-scale multi-stage reactors are shown in **Table 4.11**. The observation that approximately 33% of PS was unbiodegradable and not available for SRP was factored in COD: SO_4 utilisation rates for both the pilot-scale and technical-scale reactors and the following ratios (**Table 4.11**) were obtained.

Table 4.11 COD: SO_4 utilisation ratios for the Pilot-scale and Technical-scale Multi-stage Reactors. RSBRc= Column Upflow Recycling Sludge Bed Reactor; RSBRd= Dortmund-type Upflow Recycling Sludge Bed Reactor.

	Pilot-scale Operation		**Technical-scale Operation**		
Period	As Multi-stage Reactor	RSBRc	Period	As Multi-stage Reactor	RSBRd
Phase 1	-	0.9	Day 1-93	1.45	1.03
Phase 2	1.08	1.1	Day 43-93	0.96	0.72
Phase 3	0.68	-			

The above $COD_{utilised}:SO_{4removed}$ ratios are generally higher than the theoretical ratio of 0.67 (Greben *et al.,* 2004). Sulphidogenesis prevails at COD: SO_4 ratios of 1 and below (Collaren *et al.,* 1998). At a ratio of 0.67, there is theoretically sufficient sulphate available for SRP to utilise the available COD (Rinzenma and Lettinga, 1998). However, the utilisation and competition with other methane producing bacteria (MPB) for the available carbon source increases at a COD:SO_4 feed ratio greater than 0.67 (Greben *et al.*, 2004). At higher $COD_{utilised}:SO_{4removed}$ ratios over the theoretical value of 0.67, it is proposed that methanogens could have participated in the removal of soluble substrate. However, no gas measurements were carried out to investigate the production of methane in the reactors and the gas bubbles usually associated with methanogenic activity were not observed. Other factors that may determine the outcome of the competition between SRP and MPB in high rate anaerobic digesters include experimental run time (Harada *et al.*, 1994; Omil *et al.*, 1998), inoculation with new bacterial species (Omil *et al.*, 1997) and operational conditions such as pH (Visser *et al.,* 1996) and temperature (Visser *et al.*, 1992).

The results obtained for both the pilot-scale and technical-scale studies were comparable at the COD: SO_4 feed ratio of 2:1 (**Table 4.12**). In both studies, percentage sulphate removal ranging between 57-82% was achieved. The individual unit operations at both the pilot-scale and the technical-scale reactors also showed comparable performance (**Table 4.13**). However, it can be observed that sulphate removal in the STR (technical-scale) was higher during day 45-93 than in the RSBRd. This was attributed to the augmentation of sludge within this unit over this period.

Table 4.12 Comparison of mean sulphate and COD removal in the Pilot-scale and Technical-scale Multi-stage Reactors.

	Pilot-scale reactor			**Technical-scale reactor**
COD:SO4 feed Ratio	2:1	1:1.5	1:1	2:1
Mean percentage sulphate removal	69	56	28	57-82
Peak percentage sulphate removal	90	73	33	96
Mean percentage COD removal	-	63	27	59
Peak percentage COD removal	59	80	68	89

Table 4.13 Comparison of mean percentage sulphate removal in unit operations of Pilot-scale and Technical-scale Multi-stage Reactor. RSBRc= Column Upflow Recycling Sludge Bed Reactor; RSBRd= Dortmund-type Upflow Recycling Sludge Bed Reactor.

Pilot-scale Reactor				Technical-scale Reactor			
Period	RSBRc	STR	Clarifier	Period	RSBRd	STR	Clarifier
Phase 1	55	25	7	Day 1-93	36	24	12
Phase 2	46	15	5	Day 45-93	45	58	21
Phase 3	24	-	-				

4.4.4 Expected Efficiency of Sulphate Reduction and CODt Solubilisation

Table 4.14 compares percentage sulphate and COD removal recorded in previous studies on multi-stage downflow RSBR systems at bench-scale (Whittington-Jones, 2000) and preliminary pilot-scale (Corbett, 2001) studies with the results obtained in this study.

Table 4.14 Comparison of percentage sulphate and COD removal with previous studies on the Recycling Sludge Bed Reactor (RSBR) system.

	Whittington-Jones (2000)	**Corbett (2001)**	**This study**
Mean percentage sulphate removal	31-59%	65-70%	28-82%
Peak percentage sulphate removal	>80%	>80%	>90%
Mean percentage COD removal	42-70%	77%	27-59%
Peak percentage COD removal	>80%	69-78%	>80%

It can be observed that the expected percentage sulphate and CODt removal were largely met and were surpassed in some instances in both the pilot-scale and technical-scale studies, thus confirming the conclusions in Chapters 2 and 3, notably that the process could be effectively embedded in sewage treatment infrastructure. Furthermore, the sulphate removal results obtained in both these studies also compared well with results obtained with the use of other carbon and electron donor sources described in the literature (**Table 4.15**)

Table 4.15 Sulphate removal efficiency utilising simple organic carbon and electron donor sources compared to sewage sludge.

Carbon/electron donor source	$COD:SO_4$ Ratio	Percentage SO_4 Removal	Reference
This Study (PS)	2 1.5 1	69-82 (Pilot & technical-scale) 56 (Pilot-scale) 28 (Pilot-scale)	
Butyrate	1.5	67	Mizuno *et al*., 1994
Acetate	0.66	60	Bhattacharya *et al*., 1996
Acetate	0.87	55.5	Greben *et al*., 2004
Propionate	0.79	78	Greben *et al*., 2004

4.5 CONCLUSIONS

Based on the results obtained for the performance of the pilot-scale and technical-scale multi-stage reactors over the experimental period, a number of conclusions could be drawn. There was no loss in performance of the process when compared to the performance of the process in the lateral flow RSBR reported by Corbett (2001). No obvious advantages could be shown for uncoupling hydrolysis from sulphate reduction in the operation of the Rhodes BioSURE process as a multi-stage configuration. The STR and the clarifier did not add substantial advantages in terms of overall process efficiency. The biological processes inherent in the multi-stage operation of the Rhodes BioSURE process as originally conceptualised can be optimised in a single-stage reactor configuration, thereby significantly reducing construction and operational costs. The upflow RSBR was shown to be able to operate as a single-stage reactor in which hydrolysis and sulphate reduction are coupled, thereby achieving cost-saving advantages. This has implications for improving the economic sustainability of the technology when operated as a single-stage process. A trade-off would, however, be required between the operation of the upflow RSBR and the clarifier. In this case, the upflow RSBR would be operated at slower rates in order to obtain improved settling, which may be fed into agricultural or ornamental fish farming projects for employment opportunities, and thereby also contributing to the social sustainability component of the technology. Sulphate reduction was not significantly improved in a stirred tank reactor. However, it proved to be efficient in PS digestion and may therefore play an important role in PS disposal. A $COD:SO_4$ feed ration of 2:1 was found to provide optimal sulphate reduction rates and although throughput may be improved at lower rates, it was, however, shown that in the pilot-scale study that at a $COD:SO_4$ feed ratio of 1:1, the system was feed limited. Although preliminary results had been obtained for a single-stage operation at bench-scale, the results reported in the pilot- and technical-scale studies indicated the need to consider further development and optimisation of the Rhodes BioSURE Process in a single-stage configuration.

5 THE SINGLE-STAGE UPFLOW RECYCLING SLUDGE BED REACTOR: PROCESS CONFIGURATION

5.1 INTRODUCTION

The pilot- and technical-scale multi-stage process configuration reported in Chapter 4 had shown that while hydrolysis could, to some degree, be uncoupled from sulphate reduction in the Rhodes BioSURE process, it was evident that sulphate reduction performance was not significantly improved in a STR reactor environment as had been proposed by Corbett (2001). Indeed, the results had indicated that a single-stage operation within an upflow RSBR could provide the most effective process configuration of those investigated to date. In order to further develop these observations it was considered necessary to undertake a scale-down/scale-up iteration to establish that point before proceeding to the development of the full-scale process design.

5.2 RESEARCH OBJECTIVES

The following research objectives were identified:

1. To evaluate the upflow RSBR configuration as a single-stage process in which hydrolysis and sulphate reduction are coupled within the same reactor, and
2. To undertake this evaluation process in scale-down and scale-up studies through bench-scale, pilot-scale and technical-scale studies.

5.3 MATERIALS AND METHODS

5.3.1 Bench-scale Single-stage Reactor

The fed-batch bench-scale RSBRd described in Chapter 3 (Section 3.3.1.1) was reconfigured as a continuously fed upflow reactor system. A start-up feed of 4 ℓ SRP sludge, 4 ℓ PS and 8 ℓ synthetic mine water was used. This comprised 80% of the reactor volume with a sludge bed of 20 cm. Synthetic mine water with a sulphate concentration of 2000 mg/ℓ was prepared as previously described, and was fed continuously at a flow rate of 8.3 mℓ/min. PS was fed at a COD: SO_4 ratio of 1:1. Previous results had indicated that the system would be feed limited at a COD: SO_4 feed ratio of 1:1, thus enabling the evaluation of sulphate reduction performance at optimum organic substrate utilisation.

5.3.2 Pilot-scale Single-stage Reactor

The RSBRc that formed part of the pilot-scale multi-stage reactor described in Chapter 4 (Section 4.3.1, Figure 4.1) was reconfigured with modifications as a single-stage upflow unit for this investigation. The inner column was removed and the reactor fitted with a 3 cm diameter PVC feed pipe extended to 250 cm from the bottom of the reactor. The continuous recirculation loop was eliminated as it was considered that the high recirculation rate that had been maintained in the technical-scale multi-stage reactor was responsible for poor settling and the high levels of CODt in the effluents of the reactors. A start-up feed of 500 ℓ SRP sludge, 500 ℓ PS and 1000 ℓ synthetic mine water was used. This comprised 80% of the reactor volume with a sludge bed of 200 cm. Mine water and PS were prepared and fed to the reactor as described in Chapter 4 (Section 4.3.1) at a COD: SO_4 ratio of 1:1. The HRT was initially maintained at 22.9 hours and later extended to 36 hours.

5.3.3 Technical-scale Single-stage Reactor

The Dortmund-type RSBR constructed at Ancor Works as described in Chapter 4 (Section 4.3.2, Figure 4.2b) was reconfigured as a single-stage upflow reactor for use in this investigation. With the exception of the decommissioning of the submersible pump, everything else was maintained as previously described. Mine water and PS were initially fed at a COD: SO_4 ratio of 1:1 (Day 1- 14) and later changed to a 2:1 ratio when maximum sulphate removal rates at COD: SO_4 ratio of 1:1 had been re-confirmed. The HRT was maintained at 66.7 hours as lower retention times had been observed to lead to excessive washout of biomass from the system.

5.3.4 Analytical Methods

COD, Sulphate, Sulphide, VFA, Alkalinity, pH and statistical analysis were determined according to methods described in Chapter 3 (Section 3.3.2)**.**

5.4 RESULTS AND DISCUSSION

5.4.1 Bench-scale Single-stage Reactor

5.4.1.1 Sulphate and Sulphide

The sulphate removal and sulphide production results are shown in **Figure 5.1** for an uninterrupted period of 46 days operation. The influent sulphate concentration was relatively constant with mean concentration of 2258 mg/ℓ over the experimental period.

The mean effluent sulphate concentration over this period was 1201 mg/ℓ (±35), reflecting a 47% sulphate removal. However, this percentage increased during steady state operation (days 26-46) to 58% by day 46; a substantial improvement over the 13% recorded for the fed-batch RSBRd reported in Chapter 3. The mean sulphide concentration over the experimental period was 146 mg/ℓ, but increased to 185 mg/ℓ by day 46, with a peak sulphide concentration of 200 mg/ℓ.

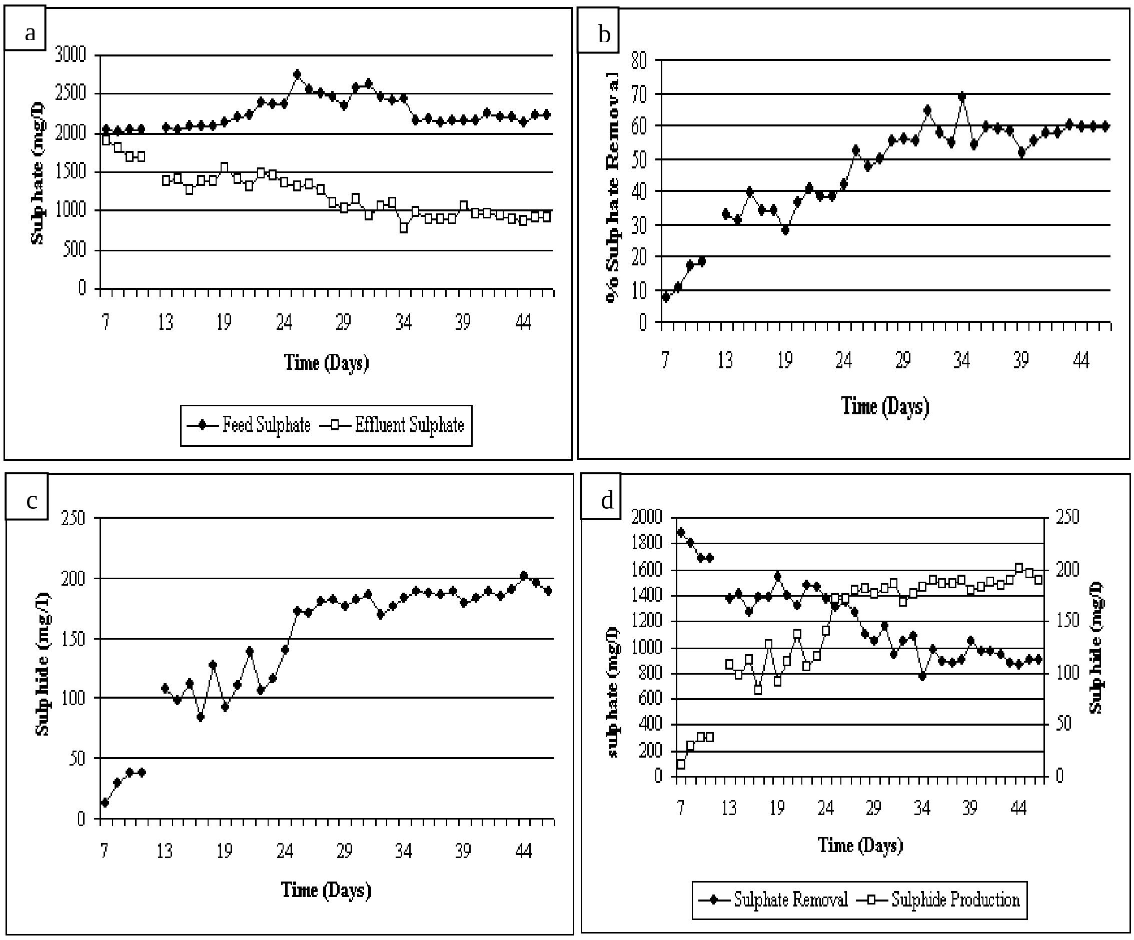

Figure 5.1 Performance of the Bench-scale Single-stage Reactor showing (a) Sulphate removal (b) percentage sulphate removal (c) sulphide production (d) sulphate removal and sulphide production.

5.4.1.2 pH and Alkalinity

The pH and alkalinity results are shown in **Figure 5.2**. Alkalinity and pH generally increased with time over the experimental period, as would be expected in a biological sulphate reduction system. The pH increased dramatically between days 7-13, where it remained stable above pH 8 between day 13-18 then remaining relatively constant at about pH 7.8 for the remainder of the experimental period.

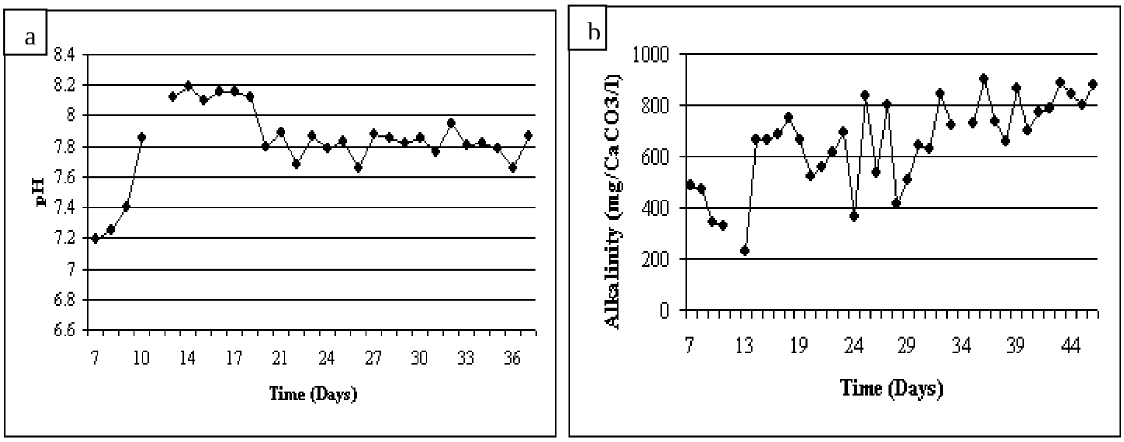

Figure 5.2 pH (a) and Alkalinity (b) in the Bench-scale Single-stage Reactor.

5.4.1.3 Volatile Fatty Acids

The VFA results are shown in **Figure 5.3** and indicate a shift from acidogenesis to sulphate reduction.

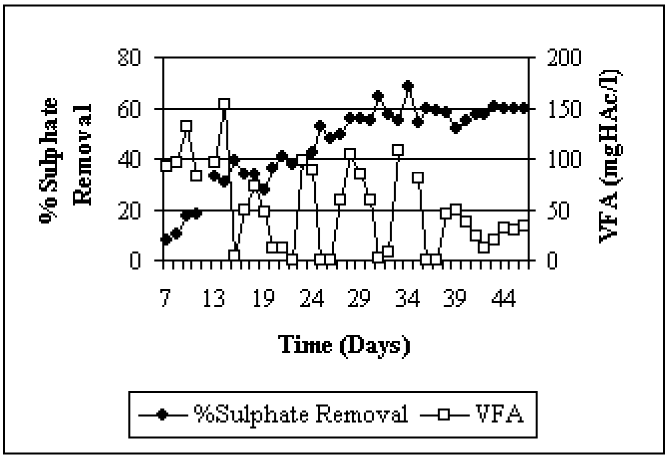

Figure 5.3 Percentage sulphate removal and VFA concentration in the Bench-scale Single-stage Reactor.

The mean VFA concentration during period 7-46 was 51 mgHAc/l which reduced to 40 mgHAc/l during days 29-46.

5.4.1.4 COD Removal

The COD removal results are shown in **Figure 5.4**. Although, the influent CODt was calculated on the basis of makeup, the results showed that the major portion of the CODt was being used in the system for biological sulphate reduction.

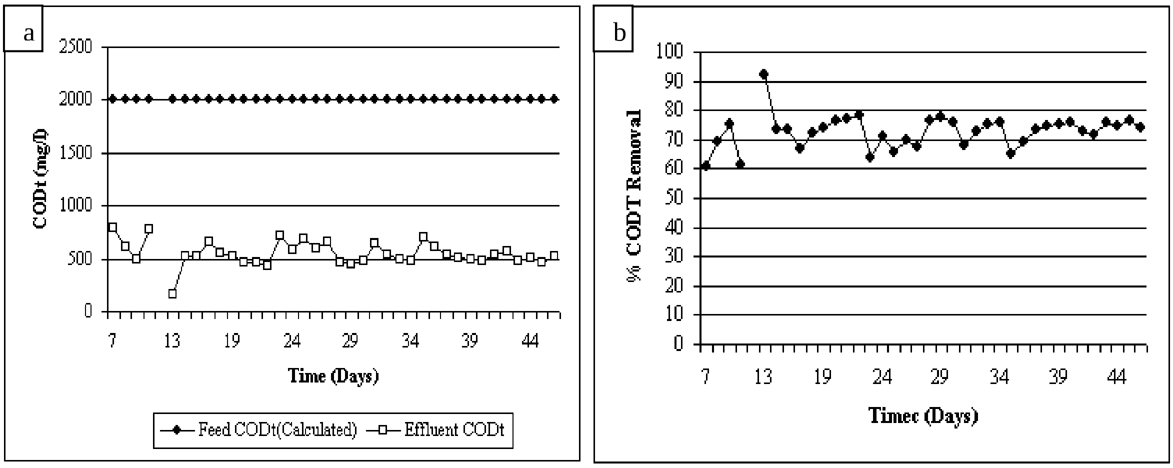

Figure 5.4 Performance of the Bench-scale Single-stage Reactor showing (a) CODt removal (b) percentage CODt removal.

While the mean CODt feed was calculated to be 2000 mg/ℓ, the mean measured CODt effluent for days 7-46 was 534 mg/ℓ, representing 73% CODt consumption. This was supported by the observation of a relatively low mean residual CODs measured in the reactor, of 314 mg/ℓ indicating a high level of CODs consumption. Importantly, settleable solids in the effluent of the reactor (**Figure 5.5**) were substantially reduced, confirming that

CODt was not being lost through washout, and indicating an improved operation for the altered configuration. A mean concentration of 0.12 mℓ/ℓ of settleable solids was determined over the period for which it was measured (**Figure 5.5**).

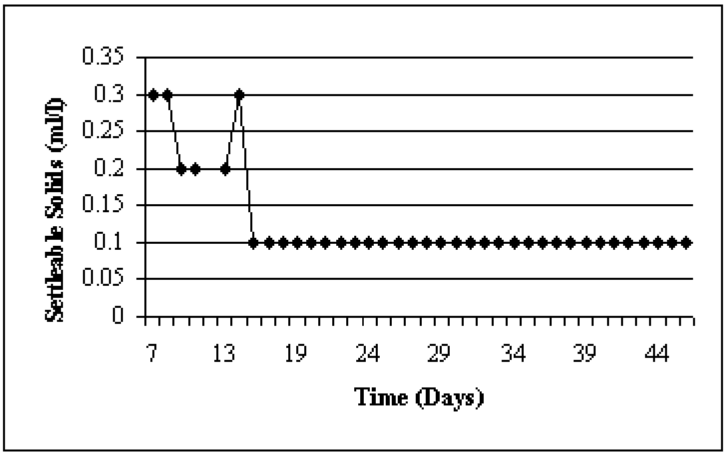

Figure 5.5 Settleable solids in effluent of the Bench-scale Single-stage Reactor.

5.4.2 Pilot-scale Single-stage Reactor

The pilot-scale single stage reactor was operated for a period of 95 days during which a number of changes were made and their effects on performance monitored. The first period ran from days 1-65 during which the sludge bed height was maintained at 200 cm. From days 65-85, the sludge bed height was increased to 275 cm by addition of PS and the head space sparged with nitrogen to prevent re-oxidation of sulphide with the formation of a film of elemental sulphur in the reactor surface. During the third period which ran from days 86 to 95, the sludge bed height and nitrogen sparging were maintained, and the HRT extended to 36 hours.

5.4.2.1 Sulphate and Sulphide

The sulphate removal and sulphide production results are shown in **Figure 5.6**. The influent sulphate concentration showed some variation with peak concentrations of above 3000 mg/ℓ at times (**Figure 5.6a**). The mean sulphate feed concentration over the experimental period was, however, 2364 mg/ℓ while the mean effluent sulphate over the same period was 1442 mg/ℓ, representing a 39% sulphate removal. The mean sulphide produced during this period was 101 mg/ℓ (±15). The operation of the plant during days 11-65 was characterised by a thick film of elemental sulphur which formed on the surface of the reactor indicating sulphide re-oxidation and that sulphate removal efficiency was thus being underestimated. During the period day 65-88, after the increment in sludge bed height and the introduction of nitrogen sparging onto the head space, sulphate removal efficiency gradually improved (**Figure 5.6a**), with a 50% sulphate removal recorded during days 72-88. The mean feed sulphate concentration over this period was 2228 mg/ℓ and the effluent concentration was 1125 mg/ℓ. The mean sulphide concentration over this period also increased to 168 mg/ℓ (**Figure 5.6c**).

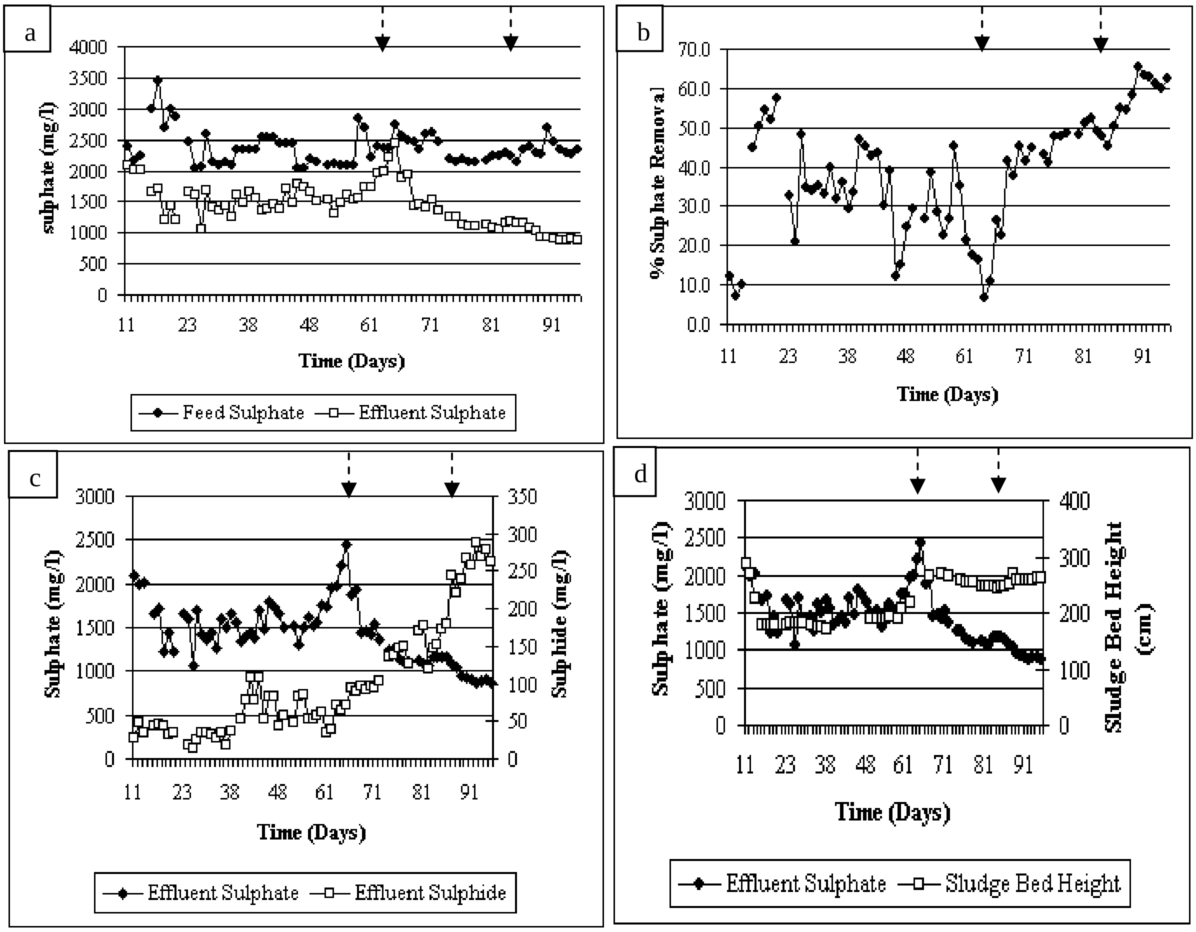

Figure 5.6 Performance of the Pilot-scale Single-stage Reactor showing (a) Sulphate removal (b) percentage sulphate reduction (c) sulphate removal and sulphate production (d) sulphate removal and sludge height. Arrows represent changes in process operation.

Extending the HRT from 20 hours to 36 hours also had a noticeable improvement on performance, with sulphate removal rising to 62%. During this period, the mean influent sulphate feed was 2378 mg/ℓ and the mean effluent sulphate concentration was 903 mg/ℓ, while the mean sulphide concentration had increased to 266 mg/ℓ. The results showed that sludge bed height was an important aspect in the successful operation of the process, together with reactor design to prevent oxygen ingress.

5.4.2.2 pH and Alkalinity

The pH and alkalinity results over the experimental period are shown in **Figure 5.7**. The pH in the reactor was observed to be unstable over the initial stages of operation up to about day 60. The effect of the changes made during days 65-85 and days 86-95 are clearly visible in **Figure 5.7a** where a concurrent increase in pH was observed for the two periods. The mean pH over the experimental period was 7 while the periods 72-88 and 86-96 registered mean pH values of 7.3 and 7.6 respectively. The effect of the increase in pH can also be seen in the sulphate removal trends (**Figure 5.7a**), where the improvement in sulphate removal can be correlated with the increase in pH. The alkalinity trends (**Figure 5.7b**) also support these observations.

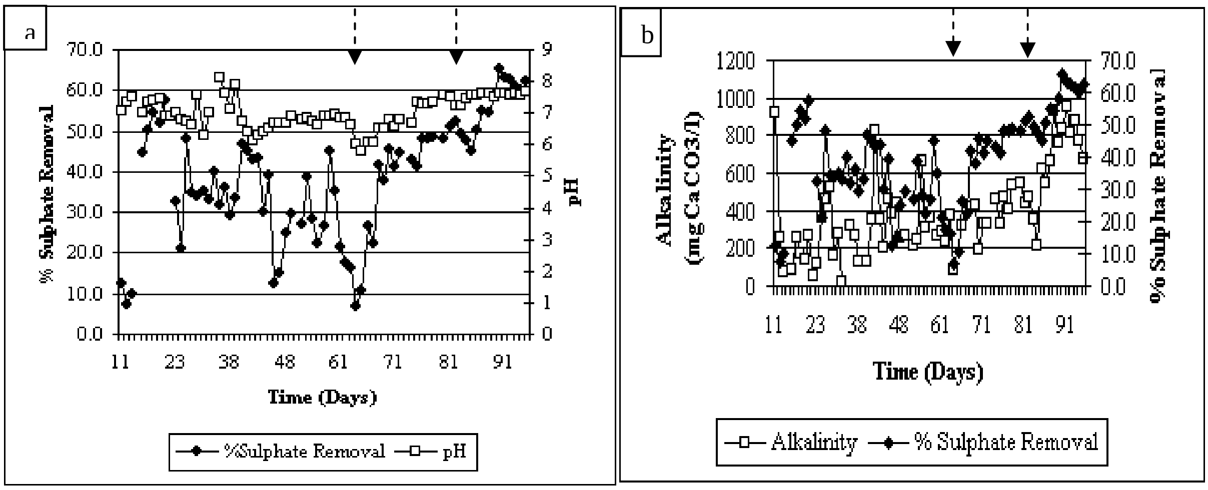

Figure 5.7 Performance of the Pilot-scale Single-stage Reactor showing (a) Percentage sulphate removal and pH (b) percentage sulphate removal and alkalinity. Arrows represent changes in process operation.

The mean alkalinity over the experimental period (days 11-96) was 399 mgH_2CO_3/l, but increased to 518 mgH_2CO_3/l and further to 814 mg mgH_2CO_3/l during days 72-88 and 86-96 respectively, reflecting the changes made over these periods.

5.4.2.3 Volatile Fatty Acids

The VFA trends are shown in **Figure 5.8**. The mean VFA concentration over the experimental period was 120 mgHAc/l, which increased slightly to 125 mgHAc/l during period 72-88 and further to 186 mgHAc/l during the period 89-96.

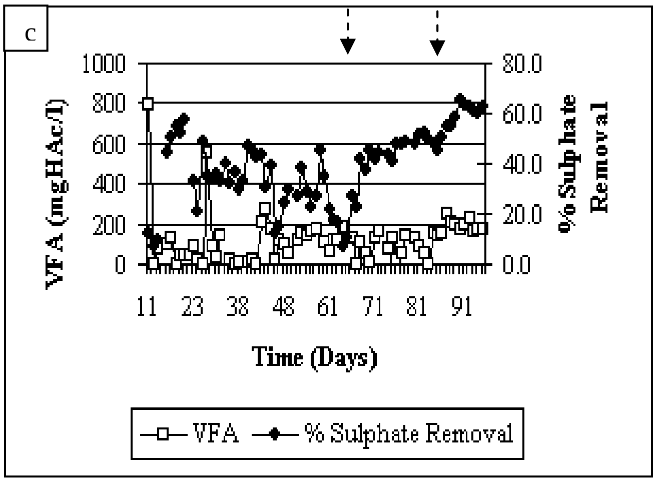

Figure 5.8 VFA generation and use, and percentage sulphate removal in the Pilot-scale Single-stage Reactor. Arrows represent changes in process operation.

5.4.2.4 COD Removal

The COD removal results are shown in **Figure 5.9**. Effluent CODt over the experimental period remained relatively constant except for days 38-42 where a dramatic increase was observed.

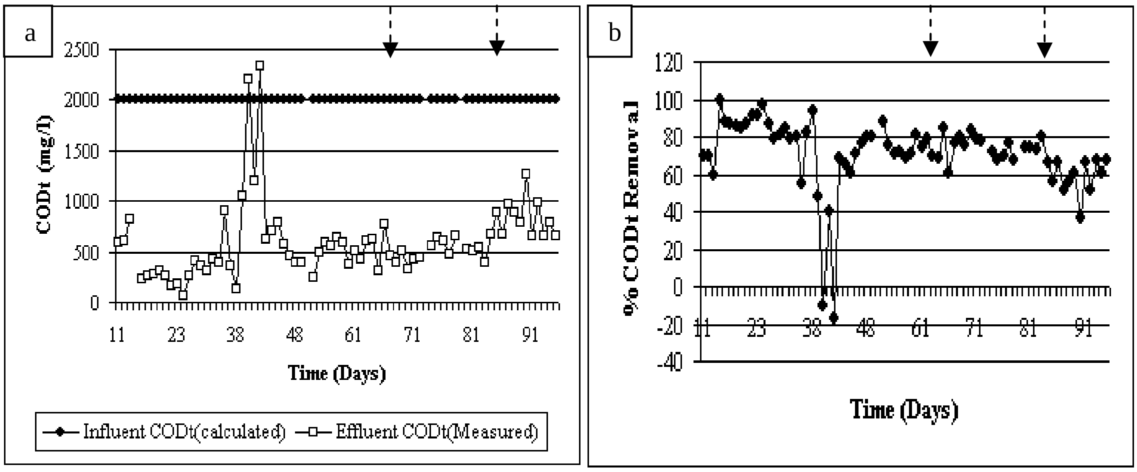

Figure 5.9 Performance of the Pilot-scale Single-stage Reactor showing (a) CODt removal (b) percentage CODt removal. Arrows represent changes in process operation.

This could have been due to the floating sludge that was observed on the surface of the reactor during these period, and no explanation could be ascribed as there was no sign of methanogenesis (gas production), although it might have been triggered by sloughing off of part of the sludge bed. This could have been caused by physical breakage of some portions of the sludge bed. The mean CODt of the effluent during the period days 11-96 was 594 mg/ℓ representing 70% CODt removal. A reduction in the mean CODt effluent was registered during days 72-88 and 89-96 representing 67% and 59%, respectively. This might have been caused by the increase in the sludge bed during this period, which reduced the settling capacity of the system.

The settleable solids results for the pilot-scale single-stage reactor are shown in **Figure 5.10** and support the observation of high CODt utilisation in the reactor. The mean concentration of settleable solids over the period days 11-91 was 0.23 mℓ/ℓ. The residual mean CODs for the three periods were 388 mg/ℓ, 428 mg/ℓ and 583 mg/ℓ respectively and showed that there was a slight accumulation of CODs within the reactors. Again, this could be attributed to the availability of more substrate as a result of increasing the sludge bed height and extending the HRT. The residual CODs also suggested that not all the CODs was being converted into VFA for use in sulphate reduction as the residual CODs in the reactor was still quite high.

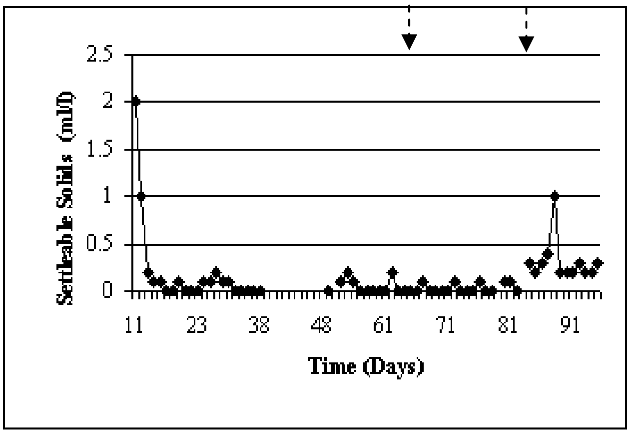

Figure 5.10 Settleable solids in the Pilot-scale Single-stage Reactor. Arrows represent changes in process operation.

However, it would have been possible to increase the efficiency of CODt utilisation and hence of sulphate reduction had the retention time been increased still further. Whittington-Jones (2000) found that approximately 90% of the residual CODt from an RSBR system was degraded when the HRT was increased to 96 hours.

5.4.3 Technical-scale Single-stage Reactor

The technical-scale single-stage reactor as described in Section 5.3.3 was piloted over a period of 418 days which were interspersed by prolonged periods of process interruption as a result of pump failure, both from the mine water supply and within the reactor itself. Of these 418 days, the reactor effectively operated for 220 days. These interruptions however provided a further opportunity for evaluation of process robustness and recovery after such failures. The results obtained for the technical-scale single stage reactor operation are shown in **Figures 5.11**, **5.12** and **5.13.** Volatile fatty acids and alkalinity were not measured over the experimental period.

5.4.3.1 Sulphate and Sulphide

The sulphate removal and percentage sulphate removal trends are shown on **Figure 5.11a** and **Figure 5.11b** respectively. Apart from the first 20 days of operation, the feed sulphate

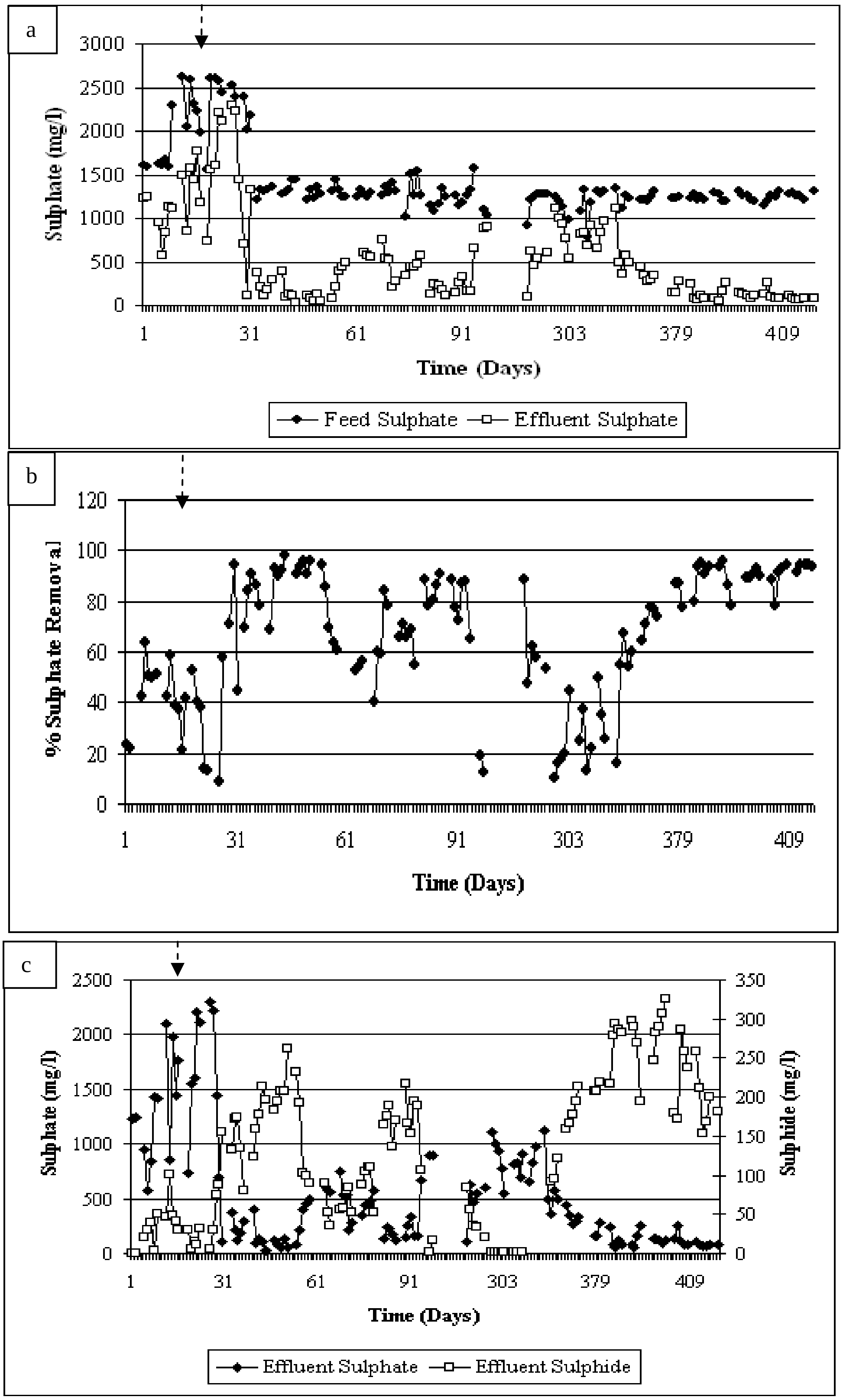

Figure 5.11 Performance of the Technical-scale Single-stage Reactor showing (a) Sulphate removal (b) percentage sulphate removal (c) effluent sulphate and sulphide trends. Arrow represents change in process operation.

concentration showed very little variation, with a mean sulphate feed concentration of 1398 mg/ℓ (±23) over the experimental period. The mean sulphate effluent concentration over the duration of the reactor operation was 543 mg/ℓ, reflecting mean 65% sulphate removal. However, effluent sulphate concentrations below 100 mg/ℓ, and occasionally as low as 40 mg/ℓ were detected in the reactor on a sustained basis, especially during the period days 369-418. The 65% sulphate removal over the experimental period was close to the 64% sulphate removal achieved during the first 94 days of operation before the first major shut down. During this period, the mean feed sulphate concentration was 1561 and the mean effluent sulphate concentration was 673 mg/ℓ, with very low effluent sulphate concentrations observed during days 30-55.

The highest mean percentage sulphate removal was registered during the period days 369-418, where the mean percentage sulphate removal of 87% was recorded. This result is particularly noteworthy in that it was achieved shortly after process resumption following a period of prolonged shut down due to pump failure. The mean sulphate feed concentration during this period was 1246 mg/ℓ while the mean effluent sulphate concentration was 156 mg/ℓ, with low peak effluent sulphate concentrations occasionally down to 30 mg/ℓ. In this reactor system, it proved impossible to prevent elemental sulphur formation on the surface, despite its being operated as a closed system. The mean percentage sulphate removal results measured are thus considered to be underestimates.

The sulphide production results shown in **Figure 5.11c** closely reflect the sulphate removal results, with the mean effluent sulphide concentration over the experimental period of 129 mg/ℓ. This increased to 226 mg/ℓ during the period days 369-418.

5.4.3.2 pH

The pH results are shown in **Figure 5.12** and indicate that the reactors operated well within the maximum pH for SRP. The mean pH over the experimental period was 8 but this dropped to 7.4 during the period 369-418, remaining well within the optimal pH range for SRP activity.

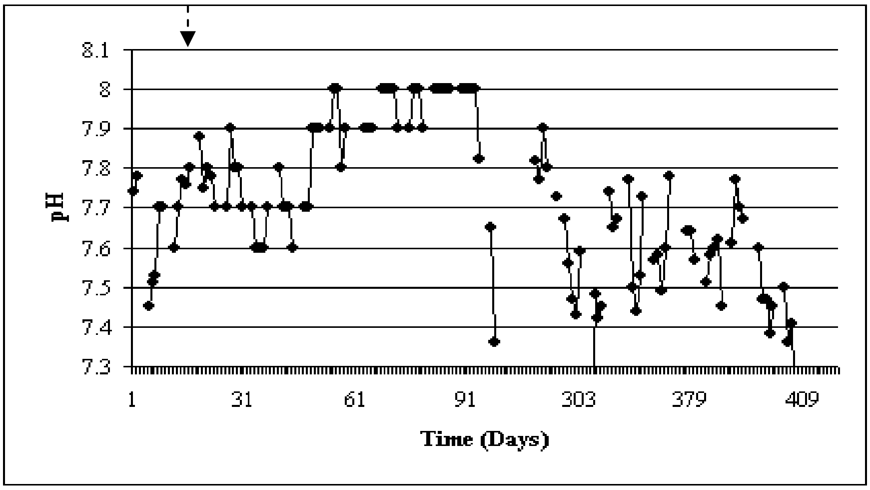

Figure 5.12 pH in the Technical-scale Single-stage Reactor. Arrow represents change in process operation.

5.4.3.3 COD Removal

A very high degree of PS solubilisation was again observed in the technical-scale single-stage reactor. However, a high concentration of CODt was also observed in the effluent over the experimental period. It should be noted that during this operation it was decided to maintain recirculation, which would have contributed to the high amount of residual CODt in the effluent from the reactor. The residual effluent CODt and CODs results are shown in **Figure 5.13**. The mean effluent CODt over the experimental period was 3853 mg/ℓ and the mean CODs concentration was 2065 mg/ℓ. During the period day 369-418, these values increased to 5309 mg/ℓ and 3108 mg/ℓ respectively. At a sludge bed height of 8 m, it is proposed that sludge would have accumulated in the reactor, resulting in very limited room for settling. This would have resulted in the high effluent CODt observed and the accompanying high residual CODs would have been due to high solubilisation rates. The effluent was also characterised by large amounts of floating debris, which would have also contributed to the higher residual CODt. The high mean concentration of settleable solids (118 mℓ/ℓ in the effluent, measured over the period days 379-418 further attested to the high level of CODt in the effluent of this reactor (**Figure 5.14**).

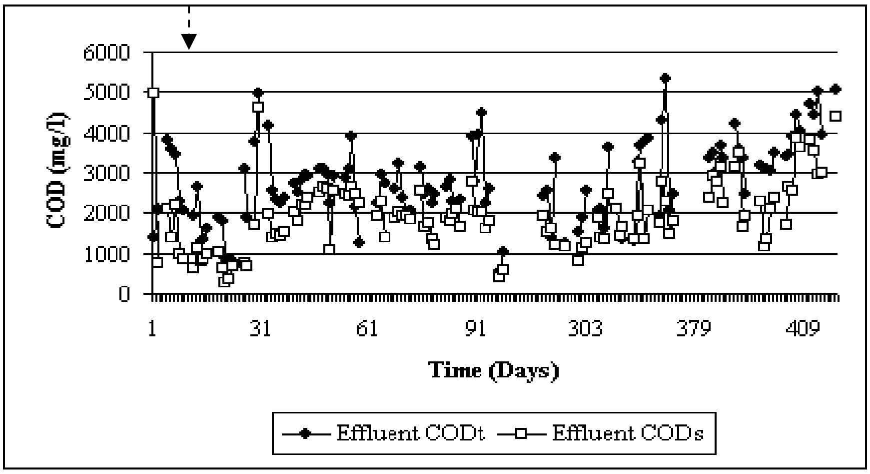

Figure 5.13 Performance of the Technical-scale Single-stage Reactor showing residual CODt and CODs. Arrow represents change in process operation.

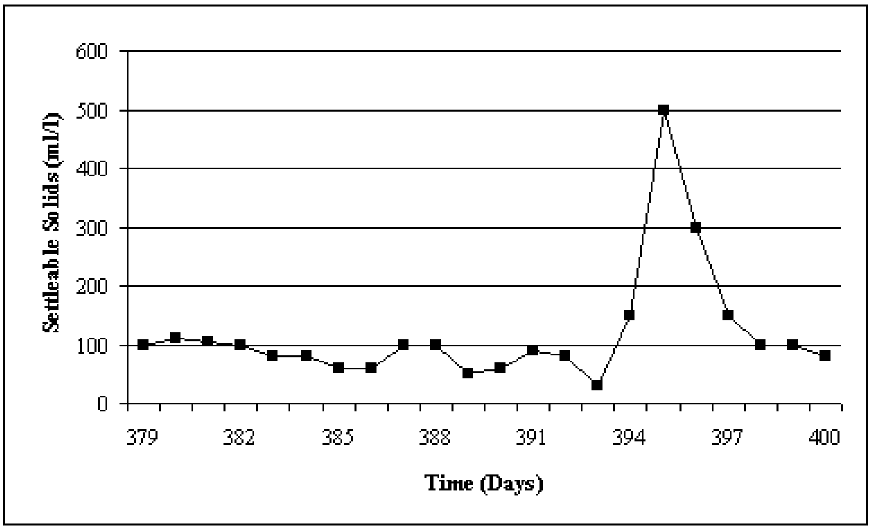

Figure 5.14 Settleable solids in the effluent of the Technical-scale Single-stage Reactor.

The peak settleable solids concentration (500 mℓ/ℓ) observed around day 395 was attributed to the observation of a sloughing off of portions of the sludge bed during this period.

5.4.4 Comparisons of Process Efficiency

Although this study compared various reactor configurations, differences in the reactor designs and problems inherent in their operations made comparisons difficult. However, comparisons were made using direct performance criteria including HRT, mean settleable solids, COD:SO_4 utilisation ratios and mean percentage sulphate removals. In addition, an efficiency factor, calculated as the product of the COD:SO_4 utilisation ratio and the HRT was formulated as a crude means of comparing process efficiency.

Table 5.1 shows estimates for sulphur mass balance, COD: SO_4 utilisation ratios, mean settleable solids concentrations in effluent and efficiency factors for the bench-, pilot- and technical-scale single-stage reactors. These were estimated for selected steady state periods of operation.

Table 5.1 Comparison of process efficiencies in the Bench-scale, Pilot-scale and Technical-scale Single-Stage Reactors for selected peak periods of operation.

	Bench-scale Single-stage Reactor	**Pilot-scale Single-stage Reactor**	**Technical-scale Single-stage Reactor**	
Steady period (Days)	29-44	89-95	1-14	369-418
COD:SO_4 feed ratio	1:1	1:1	1:1	2:1
HRT (Days)	0.83	0.95	2.8	2.8
Mean settleable solids concentration in effluent (mℓ/ ℓ)	0.12	1.5	1.8	118
Estimated sulphur mass balance (%)	77	72.4	71.5	65
Mean percentage sulphate removal	58	62	42	87
COD:SO_4 utilisation ratio	0.85	0.73	0.84	-
Efficiency factor [COD:SO_4 utilisation ratio X HRT]	0.71	1.095	2.3	-

Due to difficulties in accurately determining sulphur mass balance as a result of floating sulphur biofilm formation in the surface of the reactors, a rough sulphur mass balance was calculated for each reactor. This was determined as a percentage of the ratio of the sum of mol fraction of sulphur in effluent sulphate and the effluent sulphide concentrations to the sum of mol fraction of sulphur in the feed sulphate concentration. It was not feasible to determine the COD:SO_4 utilisation ratio for the technical-scale single-stage reactor for the period days 369-418 as the CODt in the effluent surpassed the feed CODt concentration, which would have been as a result of a number of factors including, possibly, high recirculation rates and accumulation of CODt in the reactor during this period.

It can be observed in **Table 5.1** that there was loss in performance in terms of the settling capacity of the single-stage upflow system when moving from bench- to technical-scale operations. The settling capacity was observed to decline from the bench-scale (0.12 mℓ/ℓ) to pilot-scale (0.23 mℓ/ℓ) through to the technical-scale (118 mℓ/ℓ) operations. While the relative positions of sludge bed height in these reactors and sludge recirculation rates could have played a role in the loss of settling capacity, these results raised questions on the role of sludge recirculation/recovery, and the effect of settling on process optimisation in the operation of the single-stage process.

Mean percentage sulphate removal generally increased with an increase in HRT except for the technical-scale reactor during days 1-14, which would seem to suggest that the reactor was still in the process of achieving stability. At COD:SO_4 feed ratio of 1:1, the COD:SO_4 utilisation ratios were close to the theoretical ratio of 0.67 and comparative for all the three reactors. Sulphur mass balance appeared to decrease with an increase in scale of operation, indicating, perhaps, the difficulty in maintaining tight controls over process operations at scale-up compared to scale-down operations. The results also show that the efficiency of the upflow RSB, based on the estimated efficiency factors for the various scales of operation, increased with an increase in HRT.

5.5 CONCLUSIONS

The results obtained from the scale-down/scale-up studies reported here have confirmed that the Rhodes BioSURE Process may be optimised as a single-stage process within an upflow RSBR environment. However, the observations of elevated effluent CODt raised questions on the quality of the final effluent from the single-stage process, and suggested modifications in process operation and possibly, the integration of a polishing step. Specifically, the questions that emerged included the role and nature of sludge recycle and of optimising the settling function without loss in process efficiency in the operation of the single-stage upflow RSBR. Further investigations were required in order to inform the preferred nature of sludge recycle and to validate a possible trade-off between sludge recycle, the settling function and process efficiency, especially in terms of effluent quality in the operation of the single-stage process. These would each depend on the management of the sludge bed. An attempt was thus made to examine these questions using studies of enzyme activity in the sludge bed.

6 THE USE OF SLUDGE BED ENZYME ACTIVITY PROFILE IN THE OPTIMISATION OF PROCESS CONFIGURATION

6.1 INTRODUCTION

The results obtained in Chapter 5 of this report had indicated a number of potential problems in optimising the single-stage process configuration at technical-scale. These included the role and nature of sludge recycle and of optimising the settling function in order to improve effluent quality in terms of particulates and settleable solids. In order to optimise the single-stage process at technical-scale operation, some form of comparability between the recycle of sludge from the bottom to the top of the reactor and the recycle of effluent from the top to the bottom of the reactor had to be achieved. This configuration change arose as a result of the observations that indicated the need to improve the effluent quality from the single-stage operation. Further investigations were also required to inform the validation of a possible trade-off between the recycle of sludge or effluent and the settling function in order to improve effluent quality. Given the critical role of hydrolytic enzymes in the anaerobic digestion of particulate organic matter, it was considered that an enzyme activity assay approach may provide a sensitive indicator of the relative performance of the two recycle regimes and of improving process efficiency and optimisation at the technical-scale operation.

Sulphide and other sulphur species had been shown to enhance enzyme activity in the RSBR (Pletschke *et al.*, 2002; Whittington-Jones, 2000; Whiteley *et al*., 2002; Enongene, 2003; Whiteley *et al.*, 2003; Watson *et al.*, 2004). Enongene (2003) also observed that sulphide concentration gradients were established in the sludge bed of the RSBR and increased with an increase in depth of the reactor, possibly playing a critical role in enhancing the hydrolysis of PS in the RSBR. The observation of positive correlations between enzyme activity and both sulphide and COD concentrations in a bench-scale RSBR (Enongene, 2003), appeared to support the importance of the gradients that are observed to be established in the RSBR. Enzyme activities in anaerobic and aerobic digestion systems are also generally influenced by a number of factors such as the substrate composition, the loading rates, the nature of microbial populations and environmental conditions. These among others include temperature, pH and alkalinity, degree of anaerobiosis, nutrient requirements and VFA (Moletta *et al.*, 1994; Björnsson *et al.*, 2000; Vanrolleghem and Lee, 2003). It is known that the products of hydrolysis, notably VFA, are utilised by SRP for biological sulphate reduction, and therefore, the rate of hydrolysis of PS may be directly linked to process efficiency and effectiveness.

An improved understanding of the enzyme activity function in the single-stage upflow RSBR may inform process reconfiguration and hence, process optimisation in terms of improved effluent quality at technical-scale operation.

6.2 RESEARCH OBJECTIVES

The following research objectives were identified:

1. To investigate the use of enzyme activity assay as an indicator in optimising process performance at technical-scale operation;
2. Based on optimised sludge bed operation, to reduce particulates and improve the effluent quality of the single-stage upflow RSBR configuration;
3. To improve the settling function in the single-stage upflow RSBR configuration.

6.3 MATERIALS AND METHODS

Use was made of bench-, pilot- and technical-scale reactors in the study of enzyme activity related to reactor configuration.

6.3.1 Bench-scale Single-stage Reactor

The continuously-fed RSBRd reactor (See 5.3.1) was used in this study. Samples were collected at depths from the bottom of the reactor of 30 cm (Depth 1), 20 cm (Depth 2) and 15 cm (Depth 3), during the period days 22-36, with the sludge bed height maintained at depth of 25 cm from the bottom of the reactor.

6.3.2 Pilot-scale Single-stage Reactor

The single-stage pilot-scale RSBRc reactor (See 5.3.2) was used in this study and samples were collected at depths from the bottom of the reactor of 400 cm (Depth 1), 300 cm (Depth 2) and 100 cm (Depth 3) during the period days 80-91. The sludge bed height was located at depth of 300 cm from the bottom of the reactor.

6.3.3 Technical-scale Single Stage Reactor

The single-stage technical-scale RSBRd reactor (See 5.3.3) was reconfigured and used in this study. The recycle loop was configured to recycle effluent from the top to the bottom of the reactor, as opposed to the bottom-top recycle regime previously used. Mine water was fed continuously while fresh PS was fed once daily. Both were fed from the bottom of the reactor, while the upper section of the reactor provided a settling function. Samples were collected from the influent PS and at depths from the bottom of the reactor of 9 m (Depth 1), 7.8 m (Depth 2), 5 m (Depth 3), 4 m (Depth 4), 2.5 m (Depth 5) and 1.5 m (Depth 6). The sludge bed height was located at 8 m from the bottom of the reactor.

6.3.4 Experimental Protocol

Preliminary enzyme activity profiles followed by time-course enzyme activity measurements were carried out at three depths within the bench-scale and the pilot-scale reactors. During these initial stages, chemical analysis (sulphate, sulphide, pH, VFA, alkalinity and CODt) was not undertaken. Once the recirculation regime had been established in the technical-scale reactor operated at extended steady state conditions, enzyme activity profiles were measured in conjunction with chemical analysis in samples drawn at the six depths noted. Specific activity was not measured in these studies due to the comparatively high protein content in PS and thus not being able to measure the enzyme protein component against this background.

6.3.5 Analytical Methods

α-Glucosidase, β-glucosidase and protease activity, and sulphate, sulphide, VFA, pH and alkalinity were determined according to the methods described in Chapter 3.

6.3.6 Statistical Analysis

Statistical analysis was performed according to methods described in Chapter 3 to determine significant differences in enzyme activities at different depths of the reactors. Furthermore, nonparametric correlation analysis was performed using Spearman rank order correlations to determine relationships between physico-chemical parameters and enzymes activities within the upflow RSBR.

6.4 RESULTS AND DISCUSSION

6.4.1 Bench-scale Single-stage Reactor

The enzyme activity profiles at various gradients and time course enzyme activity results obtained for the bench-scale continuously-fed RSBRd reactor are presented in **Figure 6.1**. The three enzymes assayed showed activity in the reactor at the various gradients. Enzyme activity generally increased with an increase in depth in the reactor, with depth 1 exhibiting the least activity while depth 3 showed the highest activity. α-Glucosidase activity was highest at all depths, followed by β-glucosidase activity, with protease exhibiting the least activity.

According to Nybroe *et al.* (1992), glucosidases are implicated in the degradation of starch and the hydrolysis of disaccharides arising from the degradation of polysaccharides. Enongene (2003) found that the PS at the GDW which was used in this study contained a significantly higher proportion of carbohydrate than protein fraction, with the lipid constituting the lowest fraction, which would explain the substantially higher α-glucosidase and β-glucosidase activities within the reactors compared to protease activity. All three enzymes activities were found to be significantly different at depths 2 and 3 of the reactor (ANOVA, df= 4, $p<0.05$), but were not significantly different at depths 1 of the reactor (ANOVA, df=4, $p>0.05$). α-Glucosidase showed a significantly higher activity than both β-glucosidase and protease activities at depths 2 and 3 while β-glucosidase activity was significantly higher than protease activity at depths 1 and 2.

It can also be observed that enzyme activity in the reactor remained relatively constant over the sampling period except for days 24, 29 and 30 where an increase in activity is observed for both α-glucosidase (**Figure 6.1a**) and β-glucosidase (**Figure 6.1b**) at depth 3. A similar increase in activity can also be observed at depth 3 for protease activity (**Figure 6.1c**) during days 24, 29, 30 and 31. PS feed is a variable substrate and these increments might have been due to changes in feed composition and the presence of readily available organic substrate. The mean α-glucosidase activity at depths 2 and 3 were 17 IU/mℓ and 100 IU/mℓ respectively compared to 6 IU/mℓ and 31 IU/mℓ for β-glucosidase respectively. These were significantly higher than the mean activities of 3 IU/mℓ and 2 IU/mℓ observed for α-glucosidase and β-glucosidase at depth 1 respectively. The above results indicated that enzyme activity gradients are apparently established within the sludge bed in the upflow RSBR, and that these might play a role in enhanced hydrolysis and thus also, the resulting biological sulphate reduction activity occurring in the system.

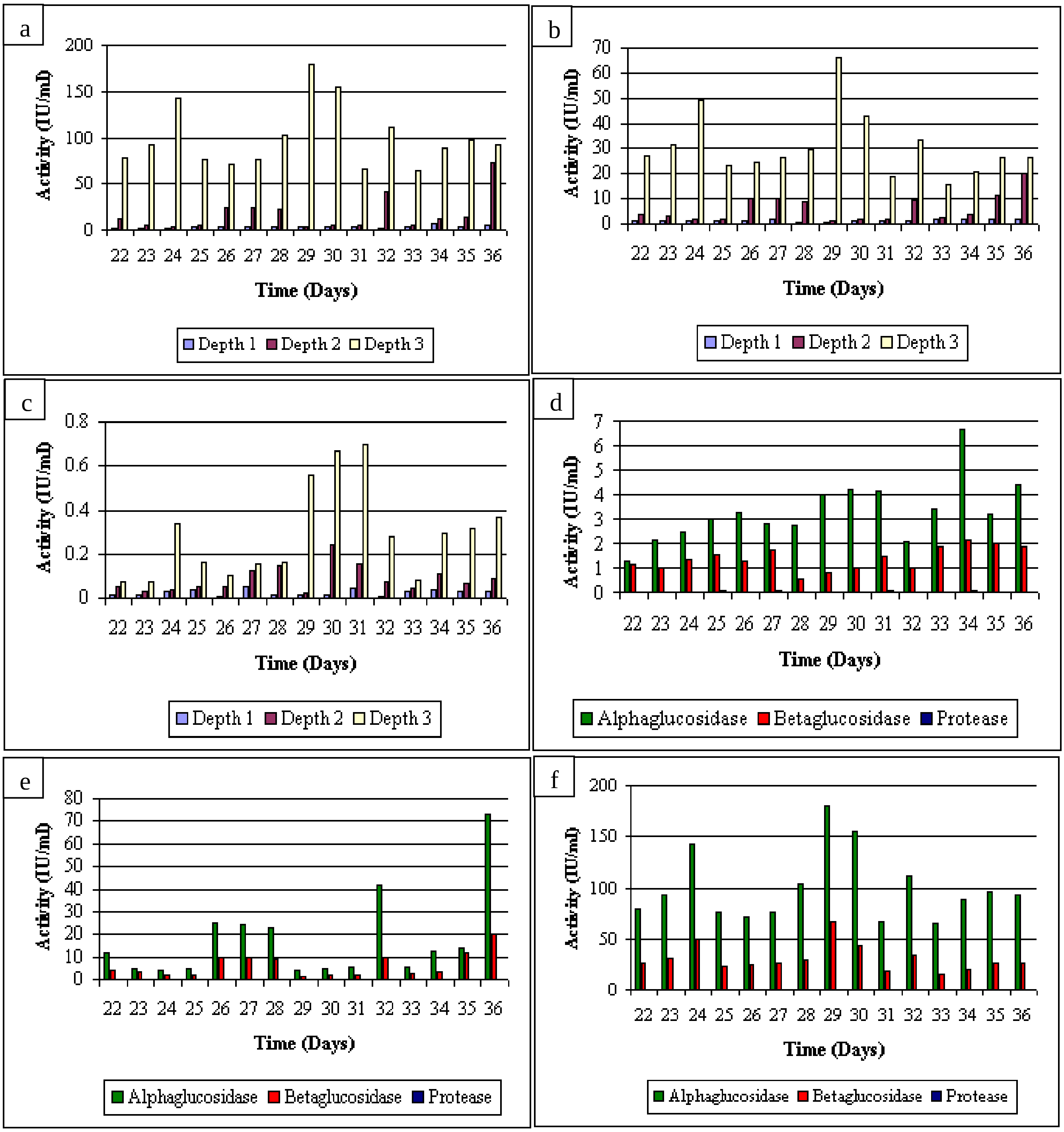

Figure 6.1 Enzyme activity profiles within the Bench-scale Single-stage Reactor showing (a) α-glucosidase activity at depths 1, 2 and 3 (b) β-glucosidase activity at depths 1, 2 and 3 (c) protease activity at depths 1, 2 and 3 (d) comparison of enzyme activity at depth 1 (e) comparison of enzyme activity at depth 2 (f) comparison of enzyme activity at depth 3.

6.4.2 Pilot-scale Single-stage Reactor

Enzyme activity was also monitored in the pilot-scale single-stage reactor for the three enzymes assayed over the sampling period and the results are shown in **Figure 6.2** and in **Table 6.1**.

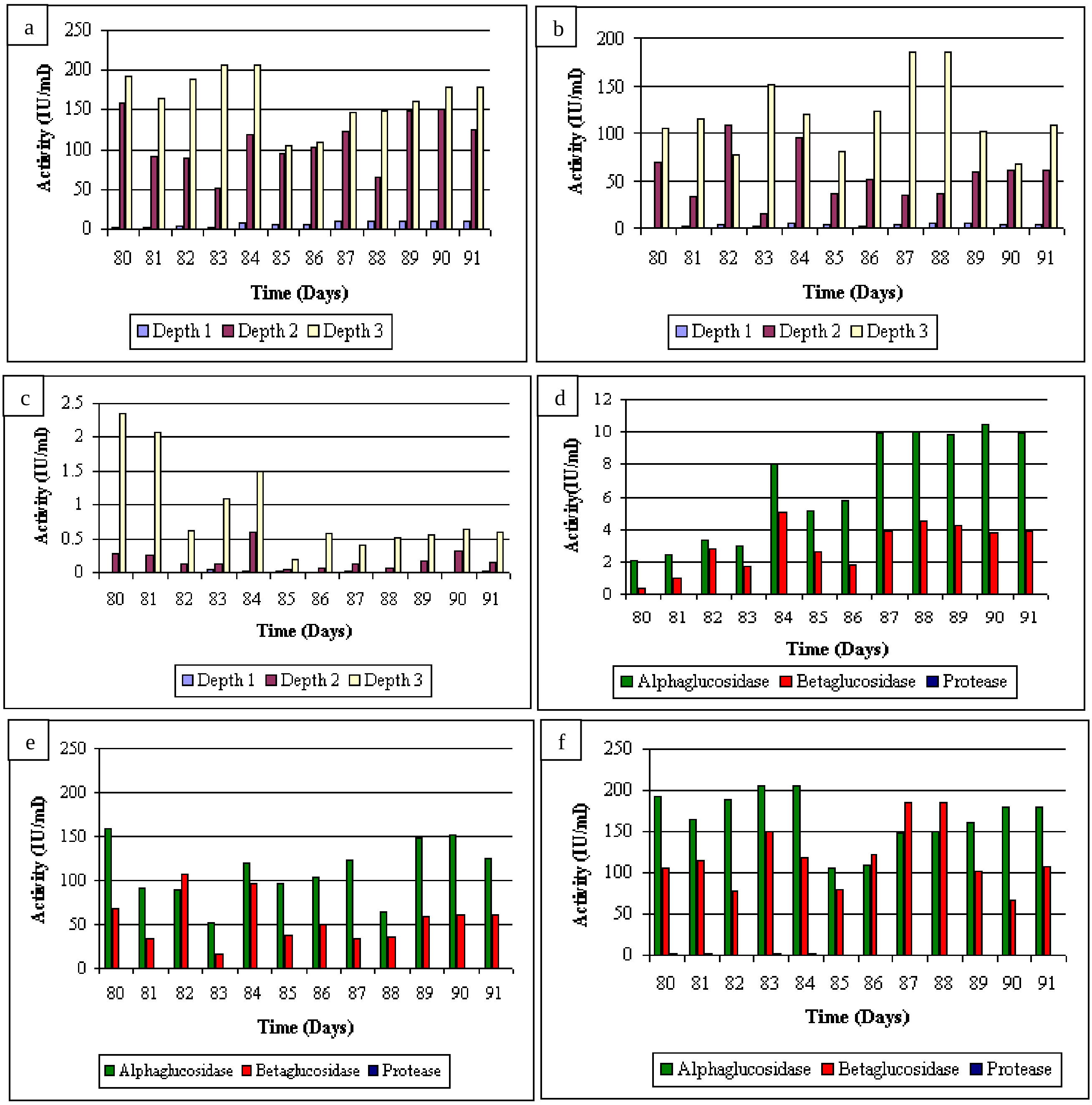

Figure 6.2 Enzyme activity profiles within the Pilot-scale Single-stage Reactor (a) α-glucosidase activity at various depths (b) β-glucosidase activity at various depths (c) Protease activity at various depths (d) Comparison of enzyme activity at depth 1 (e) Comparison of enzyme activity at depth 2 (f) Comparison of enzyme activity at depth 3.

The enzyme activity profiles observed in the pilot-scale reactor were broadly comparable to those found in the bench-scale continuously-fed reactor, with enzyme activity increasing with an increase in depth in the reactor. Again, α-glucosidase also exhibited the highest activity at all depths, with protease consistently exhibiting the lowest activity. All three enzymes showed significantly different activities at the various depth of the reactor. α-Glucosidase activity was significantly higher at depth 3 compared to depths 1 and 2 (ANOVA,df=2, $p<0.05$), and also significantly higher at depth 2 compared to depth 1 (ANOVA, df=2, $p<0.05$). A similar trend was also observed for β-glucosidase activity at all the depths in the reactor. However, protease activity was significantly higher at depth 3 compared to depth 1 and 2 (ANOVA, df=2, $p<0.05$), but was not significantly different between depths 1 and 2 (ANOVA, df=2, $p>0.05$). Furthermore, all the enzymes showed some variation with time at the various depths within the reactor (**Figure 6.2a**, **b**, **c**). α-Glucosidase activities with respect to depth are shown in **Figure 6.2a**. At depth 1, which showed the least activity, α-glucosidase activity ranged between 2 IU/mℓ and 10 IU/mℓ, with a mean activity of 7 IU/mℓ respectively.

At depth 2, α-glucosidase, showed an initial decrease in activity from 158 IU/mℓ on day 80 to 51 IU/mℓ on day 83, before registering a steady increase up to day 87, after which another decline was again observed on day 88. Thereafter, α-glucosidase activity was observed to increase at a relatively constant rate till the end of the sampling period. A mean enzyme activity of 110 IU/mℓ was recorded for α-glucosidase at depth 2. At depth 3, where enzyme activity was highest, α-glucosidase activity remained relatively constant in the range of 165 IU/mℓ to 205 IU/mℓ during days 80 to 84 before dropping sharply to 105 IU/mℓ and 108 IU/mℓ during days 85 and 86. However, α-glucosidase activity was observed to increase after day 86 and remained relatively constant in the range of 147 IU/mℓ to 179 IU/mℓ for the remainder of the sampling period. Mean activities for the three enzymes at all depths are shown in **Table 6.1**.

Table 6.1 Mean enzyme activities at various depths within the Pilot-scale Single-stage Reactor.

Depth	α-glucosidase	β-glucosidase	protease
Depth 1 (400 cm)	7	3	0.012
Depth 2 (300 cm)	110	55	0.19
Depth 3 (100 cm)	166	118	0.93

β-Glucosidase activity also showed a profile with significantly lower enzyme activity at depth 3 compared to depths 1 and 2 (ANOVA, df=2, $p<0.05$) and at depth 2 compared to depth 1((ANOVA, df=2, $p<0.05$) (**Figure 6.2b**). At depth 1, β-glucosidase activity ranged from 0.35 IU/mℓ to 5 IU/mℓ over the sampling period, with a mean enzyme activity of 3 IU/mℓ. At depth 2, β-glucosidase activity showed some variation during days 80 to 84, but remained relatively constant thereafter until the end of the sampling period. While the lowest β-glucosidase activity registered at depth 2 was 15 IU/mℓ, a peak activity of 107 IU/mℓ was observed during days 87 and 88, with a mean activity of 55 IU/mℓ registered over the sampling period (**Table 6.1**).

Protease activity observed in the pilot-scale single-stage reactor was in line with previous observations, with this enzyme showing the lowest activity at all depths of the reactor (**Figure 6.2c**). At depth 1 where the lowest activity was observed, an activity of 0.002 IU/mℓ was observed on day 89 while the highest activity of 0.02 IU/mℓ observed on day 84. The mean activity was 0.012 IU/mℓ recorded over the full sampling period (**Table 6.1**). Except for day 84 which showed an activity of 0.6 IU/mℓ, protease activity was relatively constant at depth 2 over the sampling period (**Figure 6.2c**), with a mean activity of 0.2 IU/mℓ. Depth 3 exhibited the highest protease activity, and showed some variation between day 80 and 85 (**Figure 6.2c**), but remained relatively constant till the end of the sampling period.

The enzymatic activity results for the pilot-scale reactor showed that pronounced gradients were established at various depths within the sludge bed and once again that stability within the lowest part of the bed are likely to be important considerations in designs relating to reactor configuration.

6.4.3 Technical-scale Single-stage Reactor

The preliminary enzymological investigations at bench-scale and pilot-scale operations reported above showed broadly similar trends in which enzyme activity gradients were observed to be established at various depths within the sludge bed in an upflow RSBR environment. A more detailed investigation was undertaken in the technical-scale reactor, in which the enzyme activity profiles were examined at more frequent intervals and together with physicochemical parameters including pH, alkalinity, sulphate, sulphide, CODt and VFA concentration.

Results shown in **Figure 6.3** and in **Table 6.2** indicate that both enzymes activities and physico-chemical gradients were established at all depths sampled within the technical-scale reactor. The results also suggested that enzymes may be associated with sludge flocs, as it can be observed from **Figure 6.3c** that activity appeared to decrease together with a decrease in CODt concentration from the bottom to the top of the reactor, with the highest activity and CODt observed at the bottom of the reactor. However, while enzymes activities were observed in the influent sludge sample, their activities increased substantially at depth 1.5 m (**Figure 6.3**). This was particularly evident for α-glucosidase and β-glucosidase activities, which increased by 40% and 65% respectively. Although not apparent in **Figure 6.3**, it was observed that while protease activity in the influent sludge sample was minimal (1 IU/mℓ), the activity of this enzyme was dramatically increased by as much as 700% on entry into the reactor at depth 1.5 m to 8 IU/mℓ (**Figure 6.3**). Importantly, the increase in the enzyme activity at depth 1.5 m correlates with an increase of 54% in sulphate reduction at the same depth (**Figure 6.3a**) and a marked increase in sulphide concentration from 0 mg/ℓ to 185 mg/ℓ at the same depth, suggesting that these events may be linked.

Sulphide has been reported to enhance enzyme activity in downflow RSBR systems in previous studies (Whittington-Jones, 2000; Enongene, 2003; Whiteley *et al.*, 2003). Enongene (2003) further showed that sulphide concentration increased with the depth of the downflow RSBR, indicating that the bulk of biological sulphate reduction and sulphide production occurred at the bottom of the downflow RSBR. This observation was also correlated with the increased enzyme activity observed in the presence of the increased sulphide concentration at the bottom of the reactor. Whiteley *et al.* (2003) had also demonstrated enhanced enzyme activity in the presence of sulphide and sulphite. Whiteley *et al.* (2002) further found that the activities of β-glucosidase were stimulated by specific sulphur metabolites during the hydrolysis of complex carbon under prevailing anaerobic sulphidogenic conditions.

An increase in pH of 11% (**Figure 6.3d**) and a marked increase in alkalinity of 184% (**Figure 6.3e**) were observed at depth 1.5 m in the reactor, while the decrease of 95% for VFA concentration being very marked at the same depth (**Figure 6.3f**), indicated the uptake of VFA in biological sulphate reduction activity. However, enzymes activity and sulphide, alkalinity and pH were observed to then decrease generally from the bottom to the top of the reactor. The use of multivariate data analysis has been used to understand relationships that may exist between parameters in multi-parameter systems (Doherty *et al.*, 2000; Liu *et al.*, 2003 cited in Enongene, 2003).

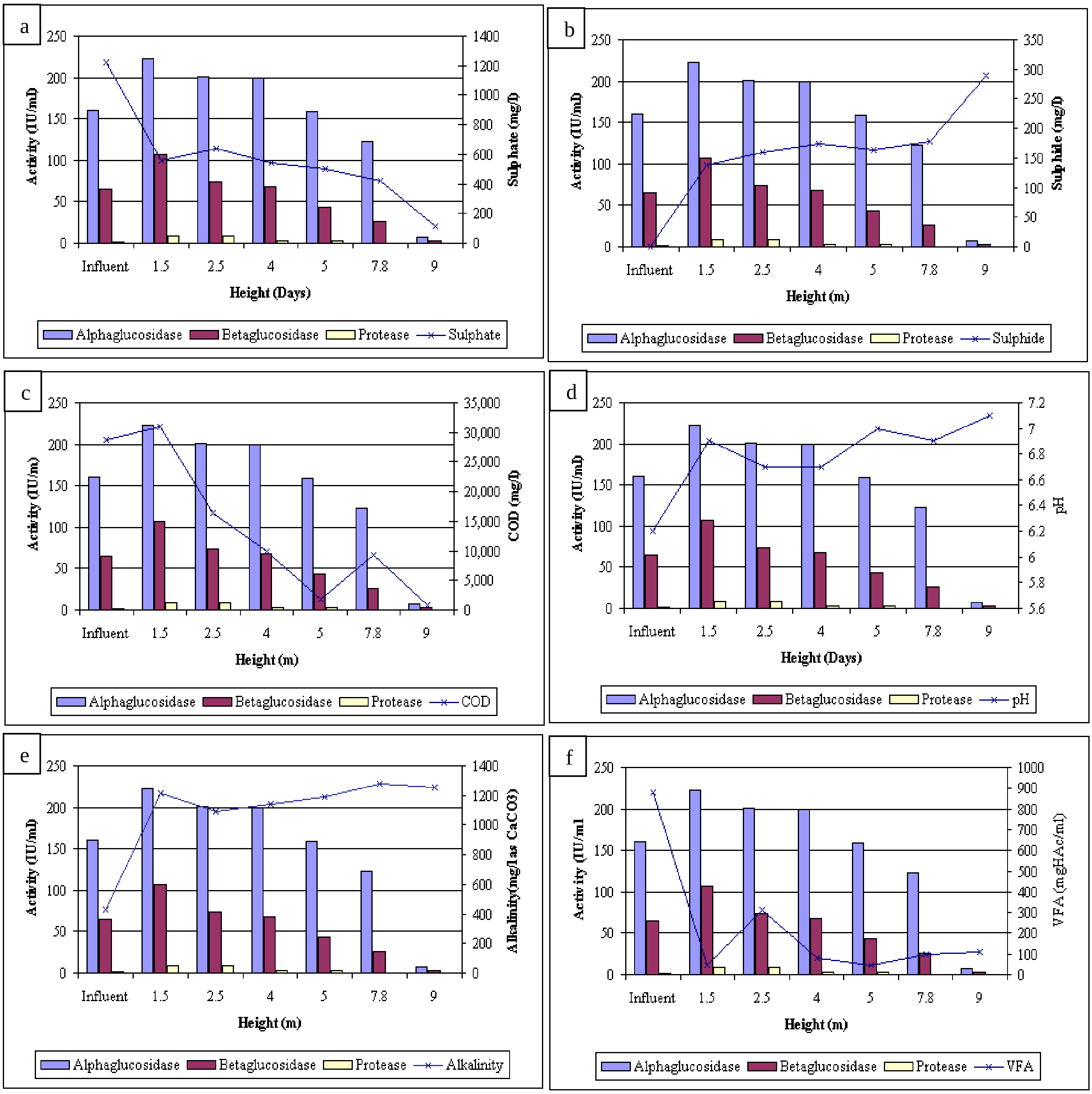

Figure 6.3 Enzyme activity and physico-chemical parameters profiles at various depths in the Technical-scale Single-stage Reactor showing (a) activity and sulphate concentration (b) activity and sulphide concentration (c) activity and COD (d) activity and pH (e) activity and alkalinity and (f) activity and VFA concentration.

The results obtained for Pearson's R correlation coefficient analysis between all pairs of combinations of the parameters within the technical-scale RSBRd showed correlations between pairs of the physico-chemical parameters, pairs of enzyme activities and between pairs of physico-chemical parameters and enzyme activities (**Table 6.2**). It can be observed from **Table 6.2** that positive correlations were found between sulphate concentration and all the enzyme activities examined within the reactor. In addition positive correlations were noted between CODt concentration and all the enzymes activities. These were significant for β-glucosidase activities but not for α-glucosidase and protease activities (**Table 6.2**). The positive correlation between CODt and enzyme activity appeared to further confirm that the enzymes were closely associated with the sludge within the reactor. Positive correlations were also observed between VFA concentration and α-glucosidase and β-glucosidase activities, but not for protease activity which showed negative correlation with VFA concentration (**Table 6.2**). A significant positive correlation was established between VFA concentration and sulphate, confirming that VFA removal was related to biological reduction by SRP within the system. Positive correlations were further observed between sulphide and depth of reactor and between pH and depth of the reactor (**Table 6.2**).

Table 6.2 Parametric (Pearson's R) correlation coefficient between physico-chemical parameters and enzyme activities of the Technical-scale Single-stage Reactor.

	Depth	α-glu	β-glu	Protease	Sulphate	Sulphide	Alkalinity	VFA	pH	CODt
Depth										
α-glu	-0.78									
β-glu	-0.87	0.91								
Protease	-0.55	0.71	**0.79**							
Sulphate	**-0.85**	0.53	0.52	0.11						
Sulphide	**0.85**	0.59	0.57	0.12	**-0.98**					
Alkalinity	0.68	-0.18	-0.24	0.15	**-0.92**	**0.85**				
VFA	-0.60	0.08	0.15	-0.14	**0.87**	**-0.78**	**-0.97**			
pH	**0.75**	-0.41	-0.41	-0.00	**-0.95**	**0.88**	**0.93**	**-0.91**		
CODt	**-0.85**	0.62	**0.81**	0.50	0.72	**-0.76**	-0.56	0.54	-0.65	

The values in bold denote a significance level at $p<0.05$, $n=7$. A positive or negative prefix indicates slopes of the regression lines at 95% confidence level. Abbreviations: α-glu = α-glucosidase; β-glu: β-glucosidase. Units: CODt (mg/ℓ); Alkalinity (as $mgCaCO_3/l$); sulphate and sulphide (mg/ℓ); all enzymes (IU/mℓ).

Positive correlations were again observed between all three enzymes, with the correlation between β-glucosidase and protease activities being significant. Furthermore, positive correlations were observed between sulphide concentration and all enzyme activities at depths 1.5 to 4, while negative correlations were found between pH and all enzyme activities. In addition, negative correlation was observed between alkalinity and both α-glucosidase and β-glucosidase activities at the various gradients within the reactor (**Table 6.2**). Significant negative correlations were observed between sulphate and sulphide, sulphate and alkalinity, and sulphate and pH. These findings are broadly substantiated by Enongene (2003), who reported positive correlations between α-glucosidase, β-glucosidase and protease activities, and sulphide and CODt concentrations, and negative correlations between these enzyme activities and sulphate concentration. The results reported here seemed to confirm that the hydrolysis of PS within the upflow RSBR is enhanced at the bottom of the sludge bed where the highest concentration of hydrolytic enzymes occurs and that enhanced enzyme activity correlates with elevated sulphide concentration. The results further seemed to suggest that the enhanced enzyme function within the upflow RSBR system was a function of a number of different mechanisms, probably physical, chemical and biological in nature. The apparent close association of enzymes with sludge flocs implies a higher enzyme concentration at the bottom of the sludge bed where sludge concentration was highest due to the gradual accumulation of sludge and this concentration gradually decreased from the bottom towards the top of the reactor. The introduction of fresh PS, containing readily biodegradable organic carbon substrate and enzymes, and sulphate into the strongly anaerobic environment at the bottom of the reactor which was rich in sulphide, alkalinity, limited concentrations of VFA, and a well adapted SRP consortium probably initiated a series of physical, chemical and biological events which culminated into the enhanced hydrolysis of PS. The enzymatic hydrolysis of particulate organic matter present in wastewater by anaerobic bacteria plays a crucial role in anaerobic degradation of waste and sludge digestion (Whiteley *et al*., 2003). Boschker and Cappenber (1998) have observed that extra-cellular enzymes may respond to changes in the amount of organic matter and composition of available substrate. Furthermore, from anaerobic digestion models, it was appreciated that both the concentration of the hydrolytic enzymes and the contact between these enzymes and their substrates had the greatest impact on the rate-limiting hydrolysis step (Jain *et al.*, 1992). It is proposed that the various fluctuations in enzyme activities observed in all the systems may be attributed to changing feed compositions and the amount of readily available substrate present in the feed. In all the reactors, enzyme activity increased with the depth of the reactor. Confer and Logan (1998) and Goel *et al.* (1998) observed that hydrolytic enzymes are associated with sludge flocs and therefore, since the accumulation of sludge increased with the depth of the reactor, higher enzyme activity was expected at the bottom of the reactors where the sludge concentration was highest. Furthermore, Goel *et al.* (1998) found that enzyme activity increased with biomass concentration in studies designed to test enzyme activity under anaerobic and aerobic conditions. An enzyme-adsorption based kinetic model (ABK model) proposed by South *et al.* (1995) also showed that the rate of hydrolysis for insoluble substrate increased with an increase in enzyme concentration and an increase in the amount of available biodegradable adsorption sites (smaller particle sizes and higher content of degradable components). Sulphidogenic reactors were demonstrated to exhibit sludges with smaller mean floc sizes as a result of higher rates of sludge fracturing than non-sulphidogenic reactors (Whittington-Jones, 2000). Given the observation that the bulk of hydrolytic enzymes are closely associated with sludge flocs, it was expected that the higher degree of floc fracturing observed within the RSBR and its propensity to retain such fractured sludge flocs at the bottom of the reactor would lead to substantially higher enzyme activities at the bottom of the reactors, leading to the enhanced hydrolysis of PS observed in both downflow and upflow RSBR systems.

6.5 CONCLUSIONS

Preliminary investigations of three key enzyme activities at various depths within upflow RSBR systems operated at bench- and pilot-scale, and a detailed analysis of enzyme activities and physico-chemical parameters at various depths within an upflow RSBR operated at technical-scale operation were undertaken. The main objective was to investigate the use of enzyme activity assay as an indicator of performance in optimising process configuration and in so doing to improve the effluent quality from the single-stage upflow RSBR at technical-scale. The following conclusions can be drawn from the evidence gathered:

1. It was shown that marked sludge, sulphide, sulphate, VFA, pH and alkalinity gradients were established in the sludge bed of the reactor;
2. These gradients correlate well with enzyme activity gradients established in the sludge bed and gradients appear to an important role in the functioning of the single-stage upflow RSBR;
3. Enzyme activity provides a useful indicator in the optimization of reactor performance;

4. As a result of these studies, it was shown that the maintenance of stability in the base of the sludge bed, where enzyme activity was highest with top to bottom recycle of effluent and bottom feed of mine water and PS, showed substantially better performance than the disruption of the sludge bed as a result of the bottom to top recycle of settled sludge at the base of the reactor.

7 POLISHING OF PROCESS EFFLUENT

7.1 INTRODUCTION

Having reduced sulphate in the influent mine water into sulphide in the Rhodes BioSURE Process, it is necessary to remove this to effect the linearization of the sulphur cycle.

The incorporation of sustainability criteria in the development of MWTT reported in Chapter 2 had indicated that both potential toxicity of wastes and possible reuse of such wastes, as prescribed by industrial ecology principles, would be expected to contribute meaningfully to the overall sustainability of the technology under development. Gaseous and dissolved sulphides can cause material problems such as corrosion, odour nuisance, an increased COD in effluents and a risk to human health (Lee *et al.*, 1993a, b; Nielsen *et al*., 1993; Hulshoff Pol *et al.*, 1998). High concentrations of hydrogen sulphide pose a serious threat to ecosystems given toxicity to plant and animal life (van der Welle, 2004). These considerations provide an important indicator for a downstream effluent polishing step following the BioSURE Process, firstly to eliminate residual reactive sulphide and secondly to prepare the effluent for subsequent reuse. A wide range of commercialised physicochemical processes exist for recovering sulphur from sulphidic waste streams, such as absorption and adsorption processes, and a variety of liquid redox processes such as the Stretford, Lo-Cat™, Sulferox™ and the Claus processes (Rein, 2002; Zicari, 2003). However, these methods invariably involve high capital investment and operational costs, which are at odds with sustainability objectives, especially in a developing country context. Less costly methods of sulphide removal from anaerobic biological sulphate removal processes include heavy metal precipitation as metal sulphides (Widdel, 1988; Boshoff, 1999), removal of the sulphide by microaerophilic *Beggiatoa* species (Basu *et al.*, 1995) and other more recently developed biological sulphide oxidation processes designed to recover elemental sulphur, such as the gutter reactor (Molwantwa, 2005), the silicone tubular reactor (Rein, 2002) and the ABR (Bowker, 2002).

In this regard, the HRAP, the clarifier, and the biological trickle filter have been proposed as possible final effluent polishing options. The feasibility of the HRAP in this role was tested at pilot-scale by Corbett (2001). Although it was shown to work well, the large pond foot print makes this a less favourable option. More recently Enongene (2004) has investigated sulphide removal using metal hydroxide sludges generated in the HDS Process. This research, which has been undertaken as a separate project within the EBRU research group, is in the process of publication and was thus not dealt with further in this programme. However, the potential toxicity of residual sulphide and the management of possible waste spills and process overruns remains a challenge to process sustainability.

While sulphate reduction is an obligate anaerobic process, the development of SRP communities in aerobic microenvironments within aerobic systems has been reported (Hulshoff Pol e*t al*., 1998; Santegoeds *et al.*, 1998). In aerobic wastewater treatment systems, SRP may account for approximately 50% of the mineralisation of organic matter (Kühl and Jørgensen, 1992; Lens *et al.*, 1995b; Santegoeds *et al.*, 1998). Biological trickle filter bioreactors, in which the pollutant-degrading microorganisms are immobilised on a carrier material (Brauer, 1984; Stoffels *et al.*, 1998), inherently support aerobic and anaerobic zones and have been demonstrated to support a sulphur cycle at a micro scale (Lens *et al.*, 1995a).

Biological Trickle filters have been widely used in the treatment of domestic wastewater (Wates, Meiring & Barnard (Pty) Ltd, 2002) and in other specialised applications including the treatment of organic pollutants from groundwater (Langwaldt and Pubhakka, 2000) and for cyanide removal from gold milling effluents (Evangelho *et al.*, 2001).

In Chapter 5, it was shown that in a single-stage operation of the Rhodes BioSURE Process, in which the sludge bed height was properly managed for effective settling and with properly managed recycle, there may be no need for a clarifier as a polishing step for the removal of residual particulate matter. Furthermore, the clarifier would be ineffective in the removal of sulphide. The biological trickle filter has been a unit operation in very wide use in sewage treatment since the 19th century and, given the requirement to embed the Rhodes BioSURE Process within the conventional sewage treatment infrastructure, this was selected for follow-up investigation as a means of rapidly removing residual sulphide from the process effluents. This would be important in preparation of effluent for downstream reuse and as a backup measure to treat potentially toxic spills and process overruns.

7.2 RESEARCH OBJECTIVES

The objective of this study was to investigate the use of the biological trickle filter in the oxidation of residual sulphides in the Rhodes BioSURE Process effluent following a sulphide removal unit process.

7.3 MATERIALS AND METHODS

7.3.1 Technical-scale Biological Trickle Filter

The biological trickle filter used in this study is shown in **Figure 7.1** and the flow path is schematically represented in **Figure 7.2**. It was constructed from 3 cylindrical concrete pipe units with a total height of 3 m and a diameter of 2 m. The biological trickle filter was packed with quarry stone (67 mm) and the working volume was estimated to be about 1 m^3.

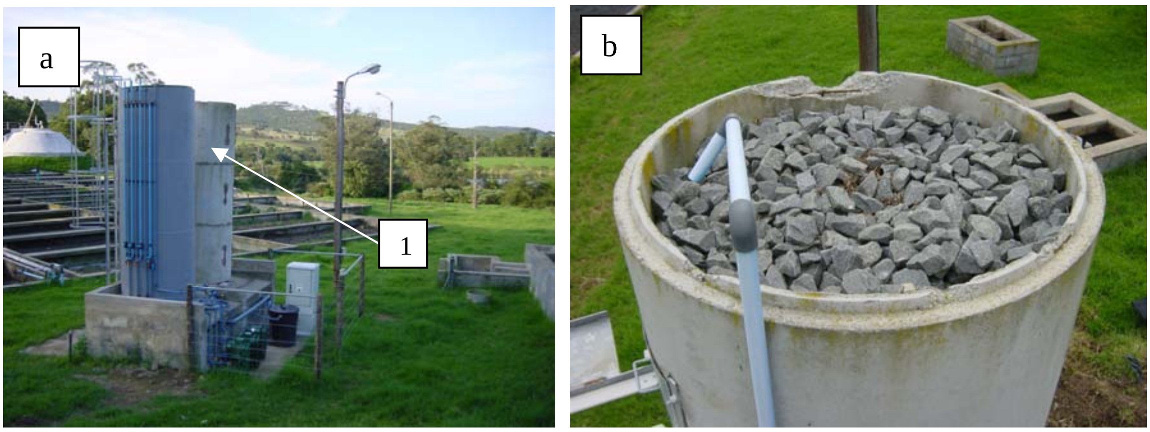

Figure 7.1 Photograph showing (a) the Pilot-scale Biological Trickle Filter (1) and (b) packed quarry stone as media.

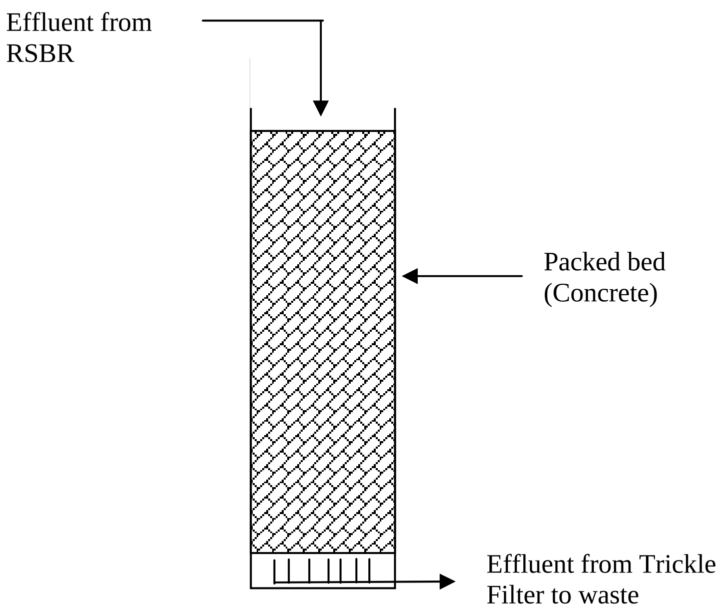

Figure 7.2 A schematic representation of the Biological Trickle Filter used in this study.

7.3.2 Analytical Methods

CODt, CODs, sulphate, sulphide, alkalinity and pH were determined according to the methods described in Chapter 3.

7.4. RESULTS AND DISCUSSION

7.4.1 Biological Trickle Filter Performance

The performance of the biological trickle filter as a polishing unit for residual sulphide was monitored over the experimental period in terms of CODt, CODs, alkalinity, and sulphate and sulphide removals. The biological trickle filter was operated for a period of 39 days and steady state results for the last 19 days are reported (**Figure 7.3)**. It should be noted that although the technical-scale RSBR was not operating at steady state conditions during the period over which this study was undertaken, it, however, did provide an opportunity to test the reactor's capacity to polish higher loads of CODt, in contrast to the expected lower CODt concentrations from an RSBR operating at steady state conditions. The feed CODt concentration varied with time over the experimental period, with the mean feed at 1943 mg/ℓ (**Figure 7.3a**).

The mean effluent CODt over the experimental period was 1472 mg/ℓ, with a mean CODt removal of 472 mg/ℓ. This is equivalent to a 24% CODt removal. On the other hand, the mean feed CODs which was 290 mg/ℓ, was reduced to 240 mg/ℓ, representing 18% removal (**Figure 7.3b**). Considering that the biological trickle filter was operated without recycle, it is likely that the percentage CODt removal achieved might have been substantially increased had effluent recycle been incorporated. However, the sulphide removal results and its implication in the overall objective of the bioprocess development of the Rhodes BioSURE Process provided an incentive to discontinue the experiment.

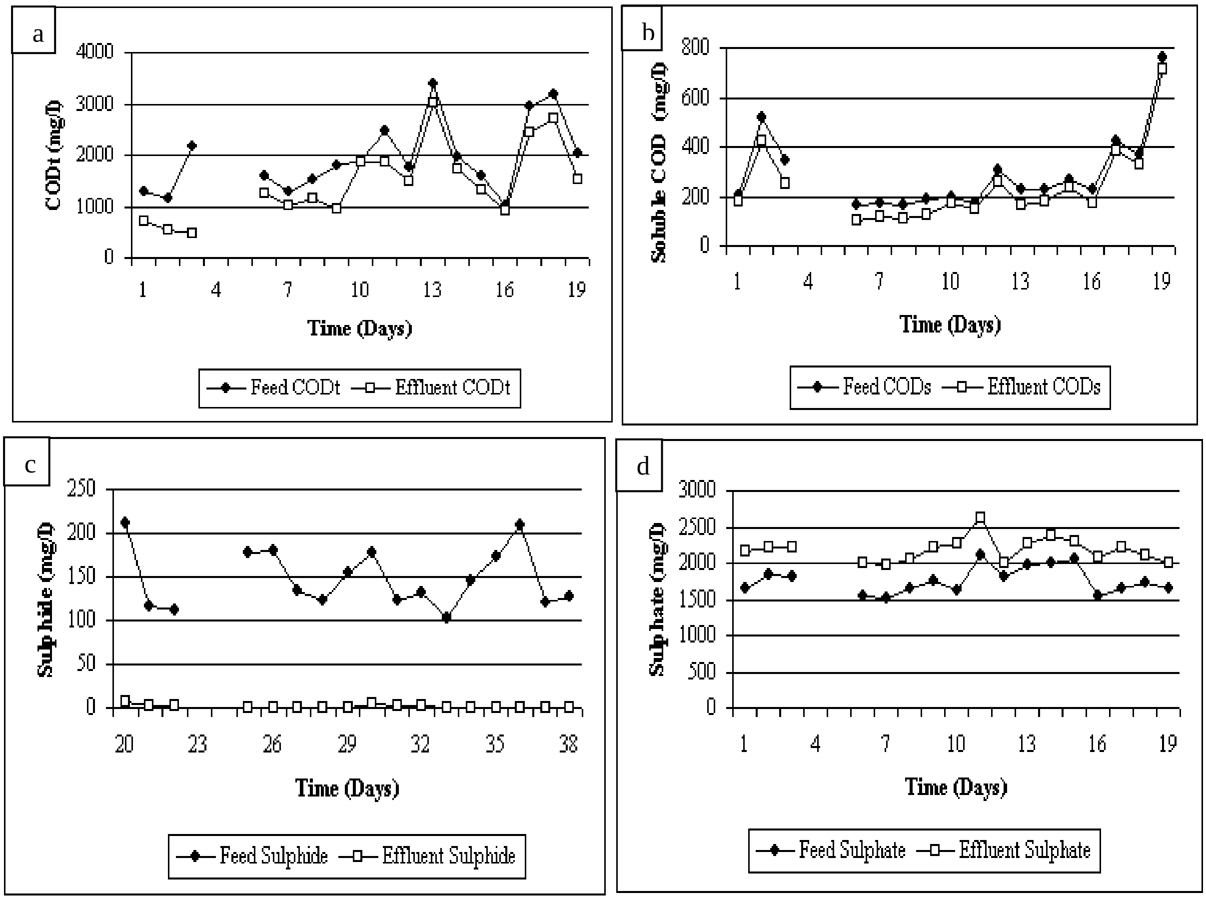

Figure 7.3 Performance of the Biological Trickle Filter as a polishing unit for the Rhodes BioSURE Process effluents showing (a) CODt removal (b) soluble COD concentration (c) sulphide removal and (d) sulphate re-oxidation during final 19 days of steady state operation.

A rapid startup of a few days was observed for H_2S removal in the trickle filter bioreactor. The bioreactor registered a sulphide removal percentage of 99% over the experimental period (**Figure 7.3c**). The mean sulphide feed concentration of 148 mg/ℓ was reduced to a mean effluent concentration of 1 mg/ℓ over the experimental period. However, the sulphate results shown in **Figure 7.3d** indicated that no sulphate removal was achieved in the reactor. On the contrary, an increase in the effluent sulphate concentration was observed. The mean feed sulphate concentration which was 1757 mg/ℓ, increased to 2183 mg/ℓ indicating a 24% increase in effluent sulphate concentration. **Table 7.1** shows a sulphur mass balance between influent sulphate and sulphide concentrations, and effluent sulphate and sulphide concentrations from the biological trickle filter. It can be observed that 99.9% sulphur recovery was accounted for, indicating that almost all of the sulphide that was recorded as sulphide removed from the system was re-oxidised to sulphate in the bioreactor.

Table 7.1 Sulphur balance in the Biological Trickle Filter.

	Feed Concentration	**Effluent Concentration**
Sulphate (As S^o)	579.81	720.39
Sulphide (As S^o)	142.08	0.96
Total	721.81	721.35
% Sulphur Recovery	99.9	

These results indicated the suitability of the biological trickle filter as an effective means of residual sulphide removal from the Rhodes BioSURE Process effluent on a large-scale application. A reduction in pH from 8.3 to 7.3 was observed between the influent and effluent of the trickle filter bioreactor (**Figure 7.4**).

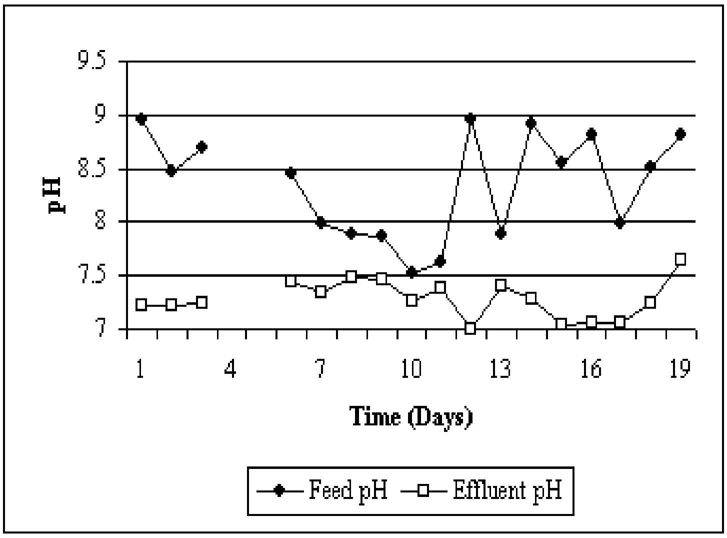

Figure 7.4 pH change in the Biological Trickle Filter.

The acidification of the medium is consistent with sulphide oxidation as illustrated in Equation **2** below:

$$2HS^{-} + 4O_2 \rightarrow 2\ SO_4 + 2H^{+} \qquad (2)$$

7.5 CONCLUSIONS

This study aimed to investigate the use of the biological trickle filter for oxidising residual sulphide from the effluent of the Rhodes BioSURE Process following sulphide recovery from other processes. The following observations can be made:

1. The biological trickle filter was shown to be effective in residual sulphide removal from the Rhodes BioSURE Process effluents;
2. The biological trickle filter was also shown to further reduce the amount of residual CODt in the process effluent by approximately 24%, although this might have been substantially improved with the incorporation of a recycle loop. While COD levels in the effluent remained a potential problem, as this did not meet the general surface water discharge limit of 75 mg/ℓ (South African National Water Act No. 36 of 1998), it is suggested that further work on high rate recycle trickle filtration would be warranted.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

Previous studies undertaken over many years at EBRU (Rhodes University) had evaluated complex organic substrates as potential carbon and electron donor sources for biological sulphate reduction. Preliminary studies with PS had been promising and had led to the development of the Rhodes BioSURE Process in the treatment of sulphate-rich mine wastewaters through bench- and pilot-scale investigations. The broad objective of the research project reported here was to investigate the final development of the Rhodes BioSURE Process at technical-scale to understand process mechanism and rate functions, and to apply these findings as a precursor to its full-scale commercial application in the South African mining industry. In undertaking this study, the need to incorporate sustainability principles into the technology development process was identified as an important objective of the research program. It was identified in particular that environmental, economic, social and technological criteria used in corporate sustainability reporting should be applied in both the developed and developing country context. Until now, attempts to incorporate sustainability thinking in MWTT process development and also in the technology evaluation and selection procedures has been handled on *ad hoc* basis by the industry. Dedicated sustainability guidelines or decision-support systems formulated to manage mine wastewater treatment process technology development and selection on a structured systemic basis have been lacking.

In terms of the sustainability objective, the following was shown:

(a) No formalised decision-support tool existed which integrated the IBL principles required to support the development and selection of MWTTs in the mining industry in South Africa;

(b) Decision-making on the technology selection process in the mining industry in South Africa appeared to be tailored towards meeting specific treatment objectives, and centred on short-term, rather than long-term goals, therefore implying a level of unsustainability in current approaches;

(c) The selection of sustainability criteria differed between a developing and developed country contexts, largely as a result of the different needs and prevailing socio-economic conditions in different regions. This indicated that it was important that technology development should take into account the different needs of application in the developing and developed world contexts;

(d) A set of core sustainability indicators were identified for use in the MWTT assessment and development undertaking. These included health and safety considerations, the reuse of treated water, employment opportunities, education and training opportunities, quantity and toxicity of wastes, energy depletion, natural resource depletion, generation of useful by-products, land area requirements, capital costs, operation and management costs, waste disposal costs, flexibility and adaptability of process, process efficiency, process effectiveness, process reliability, ease of operation, robustness of technology and process reliability;

(e) Relative weights were collated for various sustainability indicators based on the mining industry's perspective of their legal and moral obligations and on statutory/regulatory requirements.

(f) A Decision-Support System, based on the synthesis of mining industry and statutory/regulatory authority's inputs provides a novel and functional approach in aiding the identification of the most relevant sustainability indicators in a given context;
(g) While the content of the process is area-specific to South Africa, it seems that the approach has generic value that would enable its use in similar applications in a wide range of countries dealing with MWTTs.

The Sustainability Indicator Framework developed in the course of the above study focussed the scale-up process development project on the requirement of the utility operational environment. This would be required for the deployment of the technology at full-scale operation using established sewage treatment infrastructure as alternatives to novel and experimental reactor configurations that had previously been used. The following conclusions were drawn from the process scale-up/scale-down studies undertaken:
(a) The application of the Dortmund-tank reactor, the UASB and the STR, reactor configurations in common use in sewage treatment environment, were demonstrated in the operation of the Rhodes BioSURE Process at bench-, pilot- and technical-scale operations;
(b) It was shown in bench-scale operation that the hydrolysis of PS proceeds at different rates under biosulphidogenic conditions in the different reactor environments investigated;
(c) It was further shown at bench-scale and confirmed in both pilot- and technical-scale studies that biological sulphate reduction and the hydrolysis of PS could be coupled in a single reactor environment, thus informing the reconfiguration of the Rhodes BioSURE Process as a single-stage process;
(d) The sludge bed enzyme activity assay was shown to be a useful indicator of process performance and provided a potentially useful tool in process optimisation. Marked sludge, sulphide, sulphate, pH, VFA and alkalinity gradients were shown to be established in a decreasing order of magnitude from the bottom to the top of the sludge bed of the upflow RSBR and these broadly correlated with observations of enzyme activity. Enzyme activity was shown to be significantly higher at the bottom of the sludge bed, thus informing the upflow regime and thereby maintaining the integrity of the sludge bed.
(e) A trickle filter bioreactor, also a commonly used reactor configuration in sewage treatment, was shown to be effective in the rapid oxidation of sulphide enabling effective treatment of residuals and potentially toxic spills or process overruns.

8.2 FULL-SCALE OPERATION OF THE RHODES BIOSURE PROCESS

The findings and practical experiences gained from the research project reported here, led to the design, construction and implementation of the first full-scale Rhodes BioSURE Process plant at Ancor Works in Springs, with a treatment capacity of 10 Mℓ/day (**Figures 8.1** and **8.2**). A business consortium, consisting of ERWAT, Pathamanzi (Pty) Ltd, and Key Plan (Pty) Ltd collaborated in the engineering design, construction, and implementation of the full-scale plant as multiple single upflow RSBR modules and based on the findings of this study. The plant also includes a sulphide removal operation which utilises waste iron hydroxide sludge, also based on research undertaken independently at EBRU (Enongene, 2004).

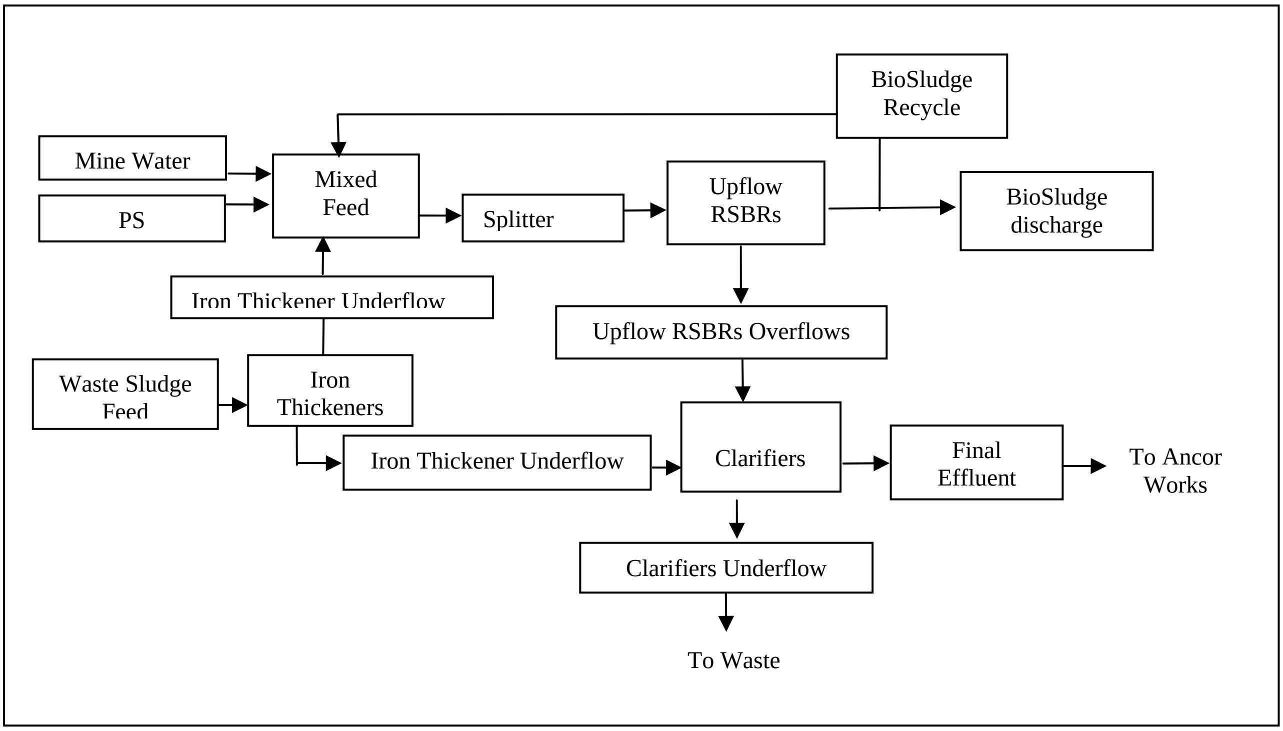

Figure 8.1 Schematic diagram of the Full-scale Rhodes BioSURE Process Plant at Ancor Works in Springs.

Figure 8.2 Photograph of the full-scale Rhodes BioSURE Process plant showing sealed individual unit upflow Recycling Sludge Bed Reactor (RSBR) modules and mine water feed tanks, clarifiers and final effluent dam in background.

Sulphate-rich mine water from Grootvlei Gold Mine and waste iron hydroxide sludge obtained from the HDS Process at Grootvlei Gold Mine are pumped 2.5 km through separate pipes into a series of holding tanks on-site at Ancor Works. PS is sourced from the primary settling tanks on-site at Ancor Works. Based on sulphate and CODt concentrations, required flow rates of the mine water and PS respectively, are calculated and pumped into a mixed feed tank from where the combined feed is split and fed into the individual upflow RSBR modules. Portions of settled sludge at the bottom of the upflow RSBR reactors are recycled to the mixed feed tank while the remainder is wasted. The overflow from the upflow RSBR modules is channeled to a series of clarifiers for polishing. The HDS iron hydroxide sludge is fed into iron thickener units from where a portion of the sludge is transferred into the mixed feed tank and another portion into the clarifiers to effect sulphide removal. The final effluent from the clarifiers is transferred into an effluent dam from where it is channeled to Ancor Works and jointly disposed of with the Ancor Works final effluent.

The performance of the full-scale plant for the month of August 2006 is reported below. **Figure 8.3** shows the mine water flow into the mine water holding tanks and the total daily mine water flow processed.

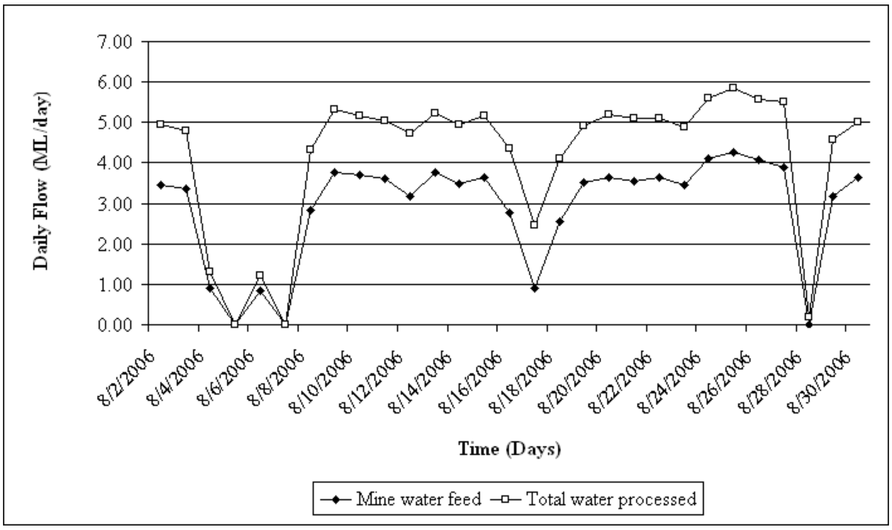

Figure 8.3 Daily mine water flow rates in the full-scale Rhodes BioSURE Process plant at Ancor Works.

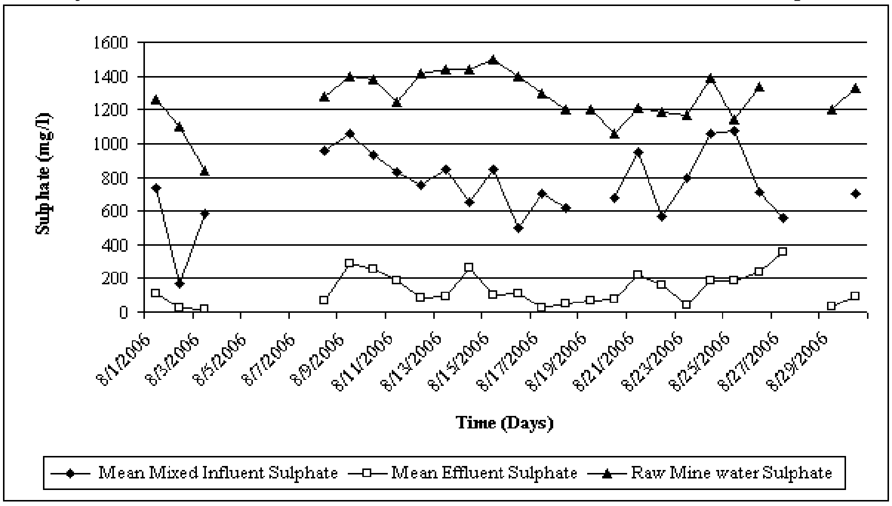

Figure 8.4 Sulphate removal results in the full-scale Rhodes BioSURE Process plant at Ancor Works for the month of August 2006.

It can be observed in **Figure 8.4** that efficient sulphate removal is achieved in the full-scale plant, with mean residual sulphate values below 200 mg/ℓ. This surpassed the target sulphate limit of 250 mg/ℓ set by the mine water treatment licence conditions imposed by the Department of Water Affairs and Forestry. While the mean sulphate concentration in the raw mine water was 1267 mg/ℓ, the mean feed sulphate concentration (mixed feed) was 751 mg/ℓ and the overall mean effluent sulphate concentration from the full-scale plant was 69 mg/ℓ, representing 91% sulphate removal. Sulphide removal results are shown in **Figure 8.5**. It can be observed that the mean effluent sulphide concentration generated from the upflow RSBR modules was 169 mg/ℓ. Following the treatment with the waste sludge, the mean effluent sulphide concentrations from the various clarifiers were 27 mg/ℓ (clarifier 1), 57 mg/ℓ (clarifier 2), 64 mg/ℓ (clarifier 3) and 11 mg/ℓ (clarifier 4), representing overall mean effluent sulphide concentration of 39.9 mg/ℓ.

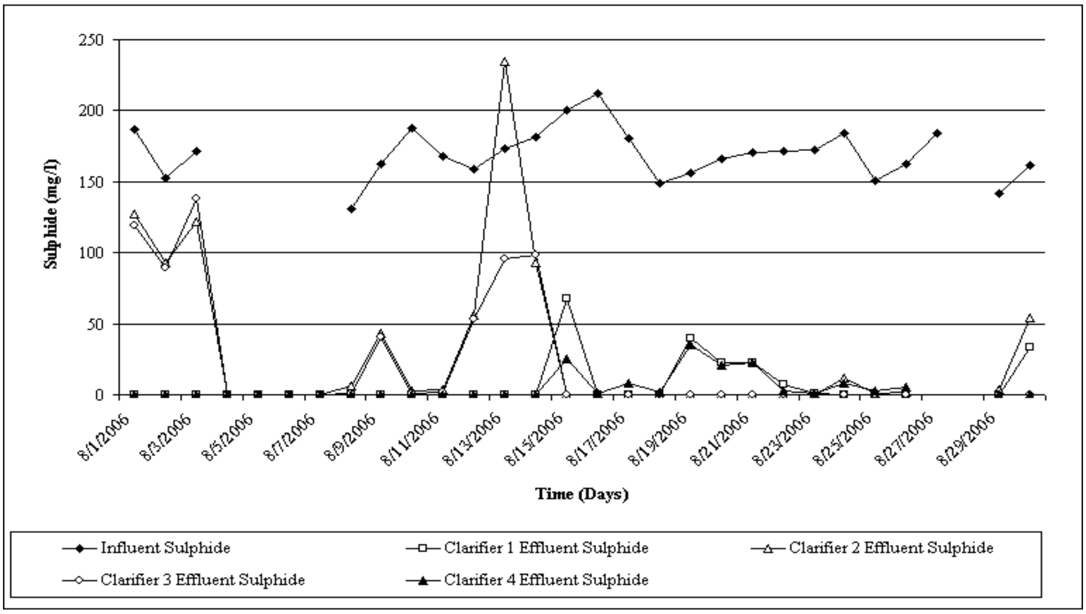

Figure 8.5 Sulphide removal in the full-scale Rhodes BioSURE Process plant at Ancor Works.

This represented an overall sulphide removal of 76% from the full-scale plant. Although the residual effluent sulphide concentration from the full-scale plant did not meet the national statutory sulphide discharge standard of 10 mg/ℓ, combining the final effluent with that of the Ancor Works largely met this requirement. It is evident that the trickle filter polishing method investigated in this study may provide a useful option.

Figures 8.6 shows results obtained for alkalinity generation in the full-scale plant. It can be observed that substantial alkalinity is generated in the process. While the mean influent alkalinity (mixed feed) was 626 mg $CaCO_3$/l, the mean effluent alkalinity was 1338 mg $CaCO_3$/l, representing an increase of 114%. This is of importance in the sulphide removal mechanism using the waste HDS iron hydroxide sludge.

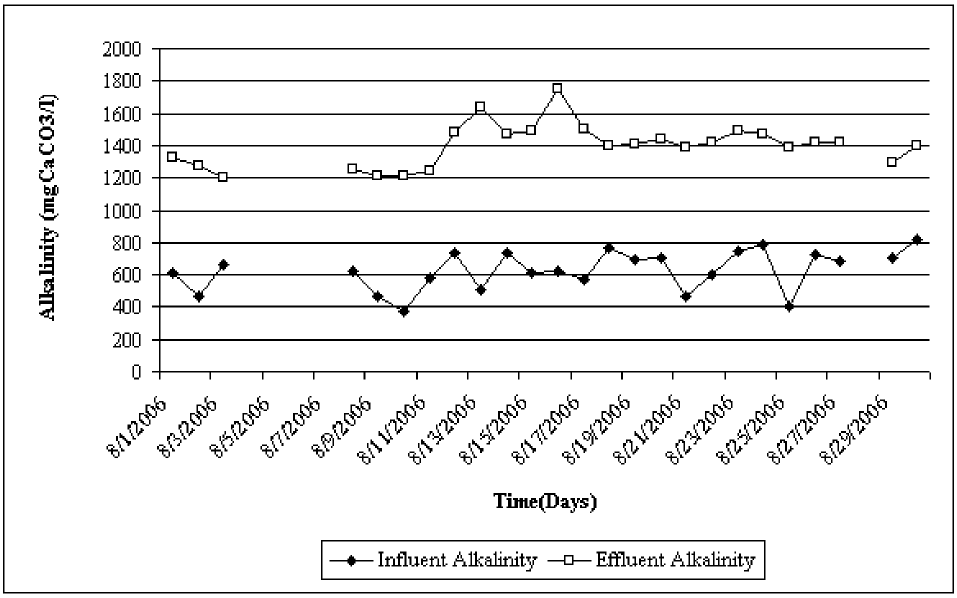

Figure 8.6 Alkalinity generation in the full-scale Rhodes BioSURE Process plant at Ancor Works.

The above technology outcome resulting from this research project largely met the key targets identified at the commencement of the study. The results enabled a sewage treatment utility operator to undertake the full-scale implementation of the technology. The operation of the full-scale plant and the results obtained thus far have indicated the technology has largely met the IBL sustainability outcomes that the research project sought to fulfil, especially in terms of technical, economic and environmental sustainability. It should be noted that a separate research project that investigated treated water reuse options in agricultural applications for the treated water by local poor communities was undertaken in collaboration with EBRU and the Department of Anthropology at Rhodes University. This work has been reported in Kumalo (2005) and was not considered in this study although recycle and reuse targets were addressed in the overall programme of which this study was part.

The research programme reported here, and the general approach that links sustainability and bioprocess technology development, makes a novel contribution to the field of MWWT. Although only a limited number of the identified sustainability indicators were used to inform the scale-up process which led to the full-scale implementation of the Rhodes BioSURE Process, the development and application of the Sustainability Indicator Framework has nevertheless been fruitful in focusing the research programme on re-evaluation of possible reactor design configurations and thereby increasing both the technical and economic sustainability of the process. It was shown that the Sustainability Indicator Framework methodology can be productively used in the improvement of technical sustainability both in the evaluation of existing applications and in focusing the development of novel MWTTs. Further research would, however, be required to test the Sustainability Indicator Framework and the Decision-Support System in other applications and effect modifications and improvements in their application in MWTT development and selection and possibly also in other areas of technology development and management.

8.3. CONCLUSIONS

This was a follow-up study to a number of previous Water Research Commission projects undertaken on the development of the Rhodes BioSURE Process and a number of conclusions emerged from the investigation:

- A systematic approach can be usefully applied in the identification of sustainability requirements to be incorporated in the development and assessment of MWTT. A Sustainability Indicator Framework methodology can be used in this regard;

- A Decision Support System provides a useful guideline in the implementation of the Sustainability Indicator Framework methodology;

- Sewage sludge provides a functional carbon and electron donor source in biological sulphate reduction in mine waste water treatment, and findings in earlier laboratory- and pilot-scale studies were confirmed at technical-scale;

- Reactor systems in common use in the hands of the utility operator, and sewage sludge can be used in operation of the Rhodes BioSURE Process for the treatment of mine drainage waste water;

- The upflow RSBR provides the optimal reactor configuration among those investigated;

- Enzyme activity analysis provides a useful tool in assessing the performance of the RSBR sludge bed;

- The biological trickle filter can be usefully applied in the polishing of final waters and in dealing with possible toxic spills form the process;

- Successful operation of the process a technical-scale provides a useful basis for proceeding to the full-scale implementation of the process in the treatment of mine drainage waste waters;

- The Rhodes BioSURE Process, as engineered within the context of the sewage utility operation, provides a basis for the long-term sustainability in the treatment of mine drainage wastewaters.

8.4 RECOMMENDATIONS

- The principal recommendation to emerge from this report was that sufficient data had been acquired to provide the conceptual framework for proceeding to the design of the full-scale Rhodes BioSURE Process plant at Ancor Works.

- The Sustainability Indicator Framework developed and described here is a first attempt at introducing a systematic approach in the incorporation of sustainability principles in the development, selection and implementation of mine water treatment technologies. Models such as these are refined through use and it is proposed that other applications of the system be undertaken in order to test the scope of its use and to add to and improve the concept.

8.5 RESEARCH PRODUCTS AND FOLLOW-UP ACTIONS

The results of the above studies provided inputs into the design, construction and commissioning of the first full-scale commercial application of the Rhodes BioSURE Process for mine wastewater treatment using sewage sludge as the carbon and electron donor source. The Grootvlei Mine and Ancor Works have been linked by pipeline and an operational capacity of 10 Mℓ/day water treated has been established with sulphate reduced from ~1300 mg/ℓ to <200 mg/ℓ. These developments constitute a novel contribution in the mine waste water treatment field.

The new full-scale plant was launched by Prof Dennis Goldberg at a ceremony at Ancor Works in May 2005 (Figure 8.7)

Figure 8.7. Participants in the launching of the new full-scale Rhodes BioSURE Process Pilot Plant at Ancor works include (L-R seated) Makhosazana Twala (Ekurhuleni Metro) and Prof Dennis Goldberg (Department of Water Affairs and Forestry) and (L-R standing) Prof Peter Rose (EBRU, Rhodes University), Mr Martin Schemers (Grootvlei Mine), Dr Adrian Pattersen (Department of Science and Technology), Dr Rivka Kfir (Water Research Commission), Mr Pat Twala (ERWAT)and MrErald Felix (SABC 50/50).

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10 APPENDICES

APPENDIX 1:

QUESTIONNAIRE

Questionnaire

Integrated Bottom Line Considerations

1. When selecting a technology for the treatment of mine drainage water, on a scale of 1-5 (where **1= Not Important**, **5 = Extremely Important**), how important do you or would you consider each of the following sustainability aspects? (Please mark choice with an **X**).

	Developing Countries		**Developed Countries**	
Parameter	**Operational Phase**	**Post-Closure**	**Operational Phase**	**Post-Closure**
Environment	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Social	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Economic	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Technical	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Legal	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Other(s)..... Please specify				
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

Social Considerations

2. When selecting a technology for the treatment of mine drainage water, on a scale of 1-5 (where **1**= **Not Important**, **5** = **Extremely Important**), how important do you or would you consider each of the following social parameters? (Please mark choice with an "**X**")

	Developing Countries		**Developed Countries**	
Social Parameter	**Operational Phase**	**Post-Closure**	**Operational Phase**	**Post-Closure**
Direct Employment	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Indirect Employment	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Health and safety	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Social perception of technology	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Potential re-use of treated water	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Education & training of external mining community	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Maintenance of social Structures	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Preservation of cultural heritage	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Political stability	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Institutional support	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Other(s)…Please specify:				
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

Environmental Considerations

3. When selecting a technology for the treatment of mine drainage water, on a scale of 1-5 (where **1**= **Not Important**, **5** = **Extremely Important**), how important do you or would you consider each of the following environmental parameters associated with inputs and products/by-products/wastes (Please mark choice with an "**X**")

	Developing Countries		Developed Countries	
Environmental Parameter	**Operational Phase**	**Post-Closure**	**Operational Phase**	**Post-Closure**
Abiotic depletion	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Natural resource depletion	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Land area required	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Ecotoxicity potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Phytotoxicity potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Energy depletion potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Global warming potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Acidification potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Nitrification potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Eutrophication potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Bioaccumulation potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Ozone depletion potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Photochemical oxidant creation potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Re-usability of raw materials	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Generation of useful by-products	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Quantity of wastes generated	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Toxicity of wastes generated	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Biodiversity	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Attraction of pests/vermin potential	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Toxicity/Hazard of raw materials	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Aesthetics	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Odour generation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Availability of special waste disposal facilities	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

Environmental Considerations Cont'd……….

	Developing Countries		Developed Countries	
Environmental Parameter	**Operational Phase**	**Post-Closure**	**Operational Phase**	**Post-Closure**
Other(s), Please specify below				
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

Financial Considerations

4. When selecting a technology for the treatment of mine drainage water, on a scale of 1-5 (where **1= Not Important**, **5 = Extremely Important**), how important do you or would you consider each of the following financial parameters associated with the technology (Please mark choice with an "**X**")

	Developing Countries		Developed Countries	
Financial Parameter	**Operational Phase**	**Post-Closure**	**Operational Phase**	**Post-Closure**
Capital costs	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Operation and maintenance costs	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
* Waste disposal costs	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
* Cost of spare parts	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Licence fees	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Decommissioning costs	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Other(s)…Please specify below				
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

Technological Considerations

5. When selecting a technology for the treatment of mine drainage water, on a scale of 1-5 (where **1**= **Not Important**, **5** = **Extremely Important**), how important do you or would you consider each of the following technical parameters associated with the technology (Please mark choice with an "**X**")

	Developing Countries		**Developed Countries**	
Technological Parameter	**Operational Phase**	**Post-Closure**	**Operational Phase**	**Post-Closure**
Ease of construction	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Flexibility/adaptability to future demands	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Susceptibility to mechanical failure	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Durability/life span of plant & parts	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Process Reliability	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Onsite/local solution	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Ease of operation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Ease of maintenance or replacement of parts	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Local availability of system expertise/technical know-how	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Availability of spare parts and equipment	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Reliance on labour force	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Level of automation	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Effectiveness of treatment	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Robustness of technology	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Efficiency of treatment process	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Other(s)…Please specify:				
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

APPENDIX 2

WRC STUDY 'SALINITY SANITATION AND SUSTAINABILITY' PROJECT REPORTS

The WRC study which has been summarised here developed out of a number of closely interrelated studies, undertaken for the WRC by the Rhodes University Environmental Biotechnology Group, over a 10 year period. The detailed findings associated with this work will be published separately as individual project reports. The following lists the WRC reports which cover the various investigations dealt with in the programme. The individual WRC projects under which the various studies were undertaken are listed separately below:

Report 1

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 1. Overview

Report 2

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 2. Integrated Algal Ponding Systems and the Treatment of Saline Wastewaters.
Part1: Meso-saline Wastewaters - The *Spirulina* Model.

(Project K5/495: A Biotechnological approach to the removal of organics from saline effluents - Part 1.)

Report 3

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 2. Integrated Algal Ponding Systems and the Treatment of Saline Organic Wastewaters.
Part 2: Hyper-saline Wastewaters - The *Dunaliella* Model.

(Project K5/495: A biotechnological approach to the removal of organics from saline effluents - Part 2.)

Report 4

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 1: The AIWPS Model.

(Project K5/651: Appropriate low-cost sewage treatment using the integrated algal high rate oxidation ponding process.)

Report 5

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 2: Abattoir Wastewaters.

(Project K5/658: Algal high rate oxidation ponding for the treatment of abattoir effluents.)

Report 6

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters.
Part 3: Mine Drainage Wastewaters - The ASPAM Model.

(Project K5/656: Appropriate low-cost treatment of sewage reticulated in saline water using the algal high rate oxidation ponding system.)

Report 7

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters.
Part 4: System Performance and Tertiary Treatment Operations.

(Project K5/799: Development and monitoring of integrated algal high rate oxidation pond technology for low-cost treatment of sewage and industrial effluents;
Project K5/1073: Extension of applications and optimisation of operational performance of algal integrated ponding systems technology in appropriate low-cost treatment of industrial and domestic wastewaters.
Project K5/1362: Development and technology transfer of IAPS applications in upgrading water quality for small wastewater and drinking water treatment systems.)

Report 8

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters.
Part 5: Winery and Distillery Wastewaters.

(Project K5/1073: Extension of applications and optimisation of operational performance of algal integrated ponding systems technology in appropriate low-cost treatment of industrial and domestic wastewaters.)

Report 9

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 4. The Rhodes BioSURE Process®.
Part 1: Biodesalination of Mine Drainage Wastewaters.

(Project K5/869: Biological sulphate desalination and heavy metal precipitation in industrial and mining effluents using the IAPS.)

Report 10

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and

Integrated Wastewater Beneficiation in South Africa.

Volume 4. The Rhodes BioSURE Process®.
Part 2: Enhanced Hydrolysis of Organic Carbon Substrates - Development of the Recycling Sludge Bed Reactor.

(Project K5/972: Process development and system optimisation of the integrated algal trench reactor process for sulphate biodesalination and heavy metal precipitation in mining and industrial effluents.)

Report 11

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 4. The Rhodes BioSURE Process®.
Part 3: Sulphur Production and Metal Removal Unit Operations.

(Project K5/1078: Development and piloting of the integrated biodesalination process for sulphate and heavy metal removal from mine drainage water incorporating co-disposal of industrial and domestic effluents;
Project K5/1336: Scale-UP development of the Rhodes BioSURE Process® for sewage sludge solubilisation and disposal.)

Report 12

Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and

Integrated Wastewater Beneficiation in South Africa.

Volume 4. The Rhodes BioSURE Process®.
Part 4: Treatment and Disposal of Sewage Sludges:

(Project K5/1169: Intermediate scale-up evaluation of the Rhodes Process for hydrolysis and solubilisation of sewage sludges in a sulphate reducing bacterial system.)

PROJECTS

The following lists the WRC Projects the findings of which have been detailed in the reports as outlined above:

Project K5/410

A Biotechnological approach to the removal of organics from saline effluents.

Report: 1. Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 1. Overview.

Project K5/495

A Biotechnological approach to the removal of organics from saline effluents.

Report: 2. Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 2. Integrated Algal Ponding Systems and the Treatment of Saline Wastewaters. Part1: Meso-saline Wastewaters - The *Spirulina* Model.

Report: 3. Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 2. Integrated Algal Ponding Systems and the Treatment of Saline Organic Wastewaters. Part 2: Hyper-saline Wastewaters - The *Dunaliella* Model.

Project K5/651

Appropriate low-cost sewage treatment using the integrated algal high rate oxidation ponding process.
Report 4: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part1: The AIWPS Model.

Project K5/656

Appropriate low-cost treatment of sewage reticulated in saline water using the algal high rate oxidation ponding system.

Report 6: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 3: Mine Drainage Wastewaters - The ASPAM Model.

Project K5/658

Algal high rate oxidation ponding for the treatment of abattoir effluents.

Report 5: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 2: Abattoir Wastewaters.

Project K5/799

Development and monitoring of integrated algal high rate oxidation pond technology for low-cost treatment of sewage and industrial effluents

Report 7: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 4: System Performance and Tertiary Treatment Operations.

Project K5/869

Biological sulphate desalination and heavy metal precipitation in industrial and mining effluents using the IAPS.

Report 9: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 4. The Rhodes BioSURE Process®. Part 1: Biodesalination of Mine Drainage Wastewaters.

Project K5/972

Process development and system optimisation of the integrated algal trench reactor process for sulphate biodesalination and heavy metal precipitation in mining and industrial effluents.

Report 10: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.

Volume 4. The Rhodes BioSURE Process®. Part 2: Enhanced Hydrolysis of Organic Carbon Substrates - Development of the Recycling Sludge Bed Reactor.

Project K5/1073

Extension of applications and optimisation of operational performance of algal integrated ponding systems technology in appropriate low-cost treatment of industrial and domestic wastewaters.

Report 7: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 4: System Performance and Tertiary Treatment Operations.

Report 8: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 5: Winery and Distillery Watewaters

Project K5/1078

Development and piloting of the integrated biodesalination process for sulphate and heavy metal removal from mine drainage water incorporating co-disposal of industrial and domestic effluents.

Report 11: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 4. The Rhodes BioSURE Process®. Part 3: Sulphur Production and Metal Removal Unit Operations.

Project K5/1169

Intermediate scale-up evaluation of the Rhodes Process for hydrolysis and solubilisation of sewage sludges in a sulphate reducing bacterial system.

Report 12: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 4. The Rhodes BioSURE Process®. Part 4: Treatment and Disposal of Sewage Sludges.

Project K5/1336

Scale-up development of the Rhodes BioSURE Process® for sewage sludge solubilisation and disposal.

Report 11: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 4. The Rhodes BioSURE Process®. Part 3: Sulphur Production and Metal Removal Unit Operations.

Project K5/1362

Development and technology transfer of IAPS applications in upgrading water quality for small wastewater and drinking water treatment systems.

Report 7: Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa.
Volume 3. Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 4: System Performance and Tertiary Treatment Operations.

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APPENDIX 3

RESEARCH PRODUCTS

3.1 STUDENTS TRAINED

3.1.1 Post-Doctoral Fellow

Dr N Nagabushana (2000) Carbon digestion in mine water treatment.

Dr G Enongene (2004) A novel method for the precipitation of ferrous iron and removal of sulphide from the Rhodes BioSURE Process effluent.

Dr Y van Breugel (2006) - The chemistry of complex carbon substrate mobilisation.

3.1.2 PhD Students

G Boshoff (Graduated 1998) - Development of integrated biological processing for the biodesalination of sulphate and metal-rich wastewaters.

K Whittington-Jones (Graduated 2000) - Sulpide-enhanced hydrolysis of primary sewage sludge: implications for the bioremediation of sulphate-enriched wastewaters.

C Ehlers (2003) - The integrated anaerobic/aerobic bioprocess environment and the biodegradation of complex hydrocarbon wastes.

H Roman (2004) - The degradation of lignocellulose in biologically-generated sulphidic environments.

D Sanyahumbi (2003) - Capsular immobilisation of sulphate reducing bacterial systems.

A Clarke (current) - The microbial ecology of sulphidogenic lignocellulose degradation..

J Molwantwa (current) - Sulphide oxidation and sulphur recovery in floating sulphur biofilms.

A Neba (current) - The Rhodes BioSURE Process and the development of sustainability indicators in the development of biological mine water treatment.

3.1.3 MSc Students

C J Corbett (Graduated 2001) - The Rhodes BioSURE Process® in the Treatment of Acid Mine Drainage Wastewaters.

J Gilfillan (Graduated 2000) - Biological sulphide oxidation and sulphur recovery from mine drainage wastewaters.

P Molipane (Graduated 2000) - Sulphate reduction utilising hydrolysis of complex carbon sources.

M Bowker (Graduated 2002) - The biology of floating sulphur biofilms.

G Chauke (Graduated 2002) - The molecular microbial ecology of sulphate reducing bacteria.

M Madikane (Graduated 2002) - The hydrolysis of lignin in sulphate reducing environments.

J Molwantwa (Completed 2002) - The enhanced hydrolysis of sewage sludge in sulphidogenic environments.

N Rein (Graduated 2002) - Sulphide oxidising biofilms and the biology of sulphur production.

3.2. PATENTS

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   RSA 97/4165 (final)
   Australia 711069(final)

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   RSA 98/3204 (Final).

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   RSA 98/9429 (Final)

4. Rose,P.D. and Hart, O.O. 1988. Treatment of sewage.
   RSA 98/9428 (Final).

5. Rose, P.D. 1998. Treatment of sulphate containing metaliferous wastewater.
   RSA 98/3202 (Final)

6. Rose P.D., Duncan, J.R., van Hille, R.P., Boshoff, G.A. 1999. Use of ponds to treat sulphate solutions and ASPAM process.
   RSA 99/4585 (Final). US patent pending.

7. Van Hille, R.P., Boshoff, G.A., Rose, P.D., Duncan, J.R. 1999. A continuous process for the biological treatment of heavy metal contaminated acid mine drainage water.
   RSA 99/3867.

3.3 PAPERS

1. Rose,P.D., Boshoff, G.A., van Hille, R.P., Wallace, L.M.C., Dunn, K.M. and Duncan, J.R. 1998. An integrated algal sulphate reducing high rate ponding process for the treatment of acid mine drainage wastewaters. *Biodegradation* 9:247-257.

2. van Hille, R., Boshoff, G., Rose, P. and Duncan, J. 1999. A continuous process for the biological treatment of heavy metal contaminated acid mine water. *Resource Conservation and Recycle*, 27:157-167.

3. Rein, N., Dorrington, R.A., Lewis, A., Loewenthal, R. and Rose, P.D. 2001. The sulphide oxidising biofilm reactor (SOBR): a component unit operation of the Rhodes SURE Process for Sewage Sludge Solubilisation. Chemical Technology, March/April, 2001.

4. Corbett CJ, Whittington-Jones K, Hart OO and Rose PD. 2001. Biological Treatment of Acid Mine Drainage Wastewaters using a Sewage Sludge Carbon Source. Chemical Technology, November/December 2001.

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3.4. CONFERENCES

3.4.1 Plenary and Key-note Papers

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2. Rose, P.D. 1999. Integrated biological treatment of metal and sulphate enriched drainage waters utilising low-cost complex organic carbon sources. European Union Conference on the Aznalcolar Mine Disaster. Seville, Spain, January, 1999.

3. Rose, P.D. 2000. Sulphidogenic hydrolysis of complex organic carbon - just sewage or a valuable resource in environmental remediation? 11th Biennial Congress of the South African Society for Microbiology. BIOY2K, Grahamstown, January 2000.

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5. Rose, P.D. 2002. The biological sulphur cycle: Part of the problem or basis for sustainable bioprocess innovation? WISA Biennial Conference, Durban, 19-23 May, 2002.

6. Rose, P., Corbett, C., Neba, A. and Whittington-Jones, K. 2004. Sewage Sludge as an Electron Donor in Biological Mine Wastewater Treatment: Development of the Rhodes BioSURE Process® . 8th International Minewater Congress, Newcastle, UK.

7. Rose, P.D. 2004 Acid mine drainage: Challenges for sustainability and social development. International Water Conference Berlin, 4-6 October.

8. Rose, P.D. 2005. Meeting the sustainability challenge: trends and developments in biological treatment of mine drainage in South Africa. 9th International Minewater Congress, Oviedo, Spain, 5-7 September.

9. Rose, P.D. 2006. The Rhodes BioSURE Process. Biobiz SA Conference, Durban, October.

10. Rose, P.D. 2006. From Grootvlei to Witbank – A decade of global leadership in the remediation and treatment of mine drainage wastewaters. Stander Lecture, 24 October.

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2. Boshoff, G., Duncan, J and Rose, P. 1994. The precipitation of heavy metals by sulphate reducing bacteria in a mixed bioreactor. Proceedings of Eight Biennial Congress of the South African Society of Microbiology. Rhodes University, Grahamstown, June 1994.

3. Boshoff, G., Leukes, W., Jacobs, E., Sanderson, R and Rose, P. 1994. Efficiency of zinc removal by microalgae, immobilised on hollow fibre ultrafiltration membranes. Proceedings of First WISA/MTD Seminar, Van Stadens, November, 1994.

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APPENDIX 4

TECHNOLOGY TRANSFER ACTIVITIES

The current report is a component investigation of the WRC research programme in Salinity, Sanitation and Integrated Algal Ponding Systems, as noted in Appendix 2 above. This study was based on previous developments of IAPS in treatment of saline wastewaters (WRC Project K5/495), and in turn led to a number of follow-on spinoff developments of which the Rhode BioSURE Process® became the principal focus. Technology diffusion and technology transfer activities initiated during the course of the study involved interactions with industry partners and led to scaled-up evaluations of the technology under development.

4.1 OFFICIAL OPENING OF THE RHODES BIOSURE® PILOT PLANT

The investigation of sulphate saline wastewater treatment and the resulting scale-up developments of the Rhodes BioSURE Process® largely took place at sites remote from the EBG laboratories in Grahamstown. As a result it was decided to establish a BioSURE® pilot plant on-site at the EBFS to facilitate both fundamental and up-scale/down-scale investigations.

The BioSURE® and Sulphur Biology Pilot Plants, located at the Rhodes University Environmental Biotechnology Field Station, at the Grahamstown Works, was opened during the Mine Water Conference at the BIOY2K meeting in January, 2000, by the Executive Director of the Water Research Commission, Mr P Odendaal. The event was attended by around 150 people including conference delegates from academia, industry and government. The plant has since been visited by several hundred people.

Figure A 4.1. The Rhodes BioSURE® Pilot Plant at the Environmental Biotechnology Field Station opening by the Executive Director of the Water Research Commission, Mr P Odendaal. At left Dr D Woods, Vice Chancellor, Rhodes University.

4.2 OFFICIAL OPENING OF THE FULL-SCALE RHODES BIOSURE PROCESS PLANT.

The new full-scale Rhodes BioSURE Process plant was constructed at Ancor Works, Springs. The plant was launched by Prof Dennis Goldberg at a ceremony at Ancor Works in May 2005 (Figure 8.7)

Figure 8.7. Participants in the launching of the new full-scale Rhodes BioSURE Process Pilot Plant at Ancor works include (L-R seated) Makhosazana Twala (Ekurhuleni Metro) and Prof Dennis Goldberg (Department of Water Affairs and Forestry) and (L-R standing) Prof Peter Rose (EBRU, Rhodes University), Mr Martin Schemers (Grootvlei Mine), Dr Adrian Pattersen (Department of Science and Technology), Dr Rivka Kfir (Water Research Commission), Mr Pat Twala (ERWAT)and MrErald Felix (SABC 50/50).

APPENDIX 5

RESEARCH SPIN-OFF DEVELOPMENTS

5.1 PASSIVE SYSTEMS AND THE INNOVATION FUND PROJECT

Passive treatment systems for the remediation of mine drainage wastewaters have been under investigation by William Pulles of PHD Inc. Rhodes EBG were invited to participate in the Department of Arts Culture Science and Technology (DACST) Innovation Fund award in which the commercialisation of sulphate removing passive treatment systems was to be investigated. Current research is investigating the application of a degrading bed reactor for the solid state digestion of lignocellulosic wastes as a feedstock in the passive treatment operations. The sulphate reducing degrading packed bed reactor has been based on the RSBR development associated with the BioSURE Process®. This research has led to the development of the patented IMPI Technologies system for passive treatment of mine wastewaters.

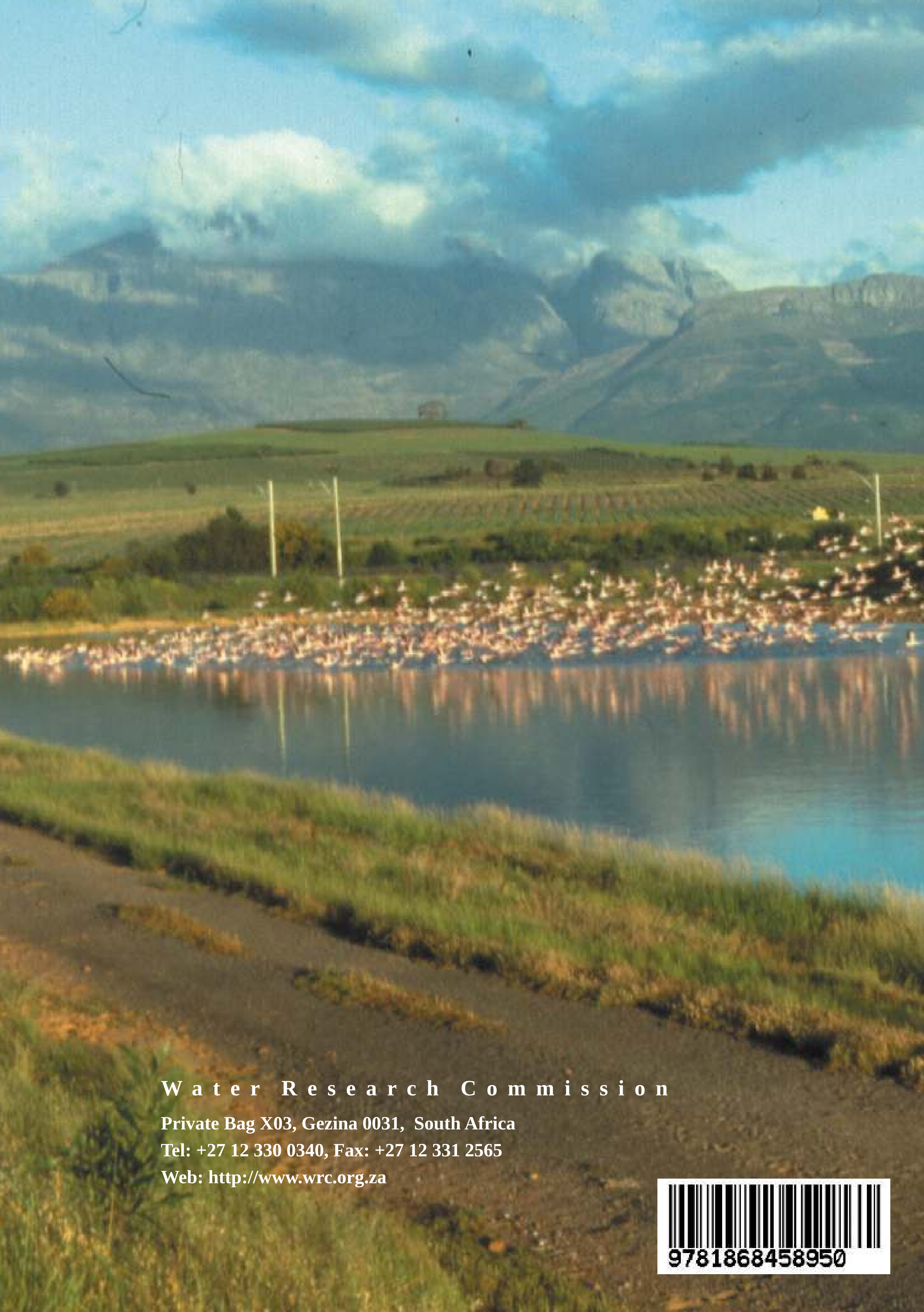
5.2 THE ASPAM PROCESS

The investigation of enhanced hydrolysis of complex organic substrates present in tannery effluents, and their use as carbon and electron donor sources, supporting high rates of sulphate reduction, provided an indication that ponding systems might themselves be used as bioreactors for the biological treatment of large-volume AMD flows. While Waste Stabilisation Pond technology has been developed over the past 40 years for a wide range of wastewater treatment applications little attention, if any, has focussed on the use of these systems for AMD remediation.

This application of Integrated Algal Ponding Systems (IAPS) was investigated in WRC Project K5/869: 'Biological sulphate desalination and heavy metal precipitation in industrial and mining effluents using the IAPS', and the use of tannery effluent and sewage sludges as effective electron donors in sulphate-salinity reduction applications was demonstrated. These studies resulted in the conceptual development of the Algal Sulphate Reducing Ponding Process for Acid Metal Wastewater Treatment (ASPAM) and are detailed in WRC report 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 3: Mine Drainage Wastewaters – The ASPAM Model'. This work has been the subject of scale-up studies in WRC Project 1621 "Development of sustainable low-cost management for saline sewage and saline mine drainage wastewaters using Integrated Algal Ponding Systems."

5.3 SULPHIDE OXIDATION AND METAL REMOVAL UNIT OPERATIONS

The biological sulphate reduction operation used in the mine waste water treatment application generates a sulphide product which requires removal in order to linearise the overall remediation operation. Heavy metals present in the influent waters also need to be removed prior to biological treatment. WRC Projects 1078, 1336, 1349 and 1545 have investigated the biological conversion of sulphide to elemental sulphur and the precipitation of metals as metal sulphides. These studies will be detailed in WRC Report TT 197/07 "The Rhodes BioSURE Process. Part 3: Sulphie oxidation and metal removal unit operations".



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9781868458950