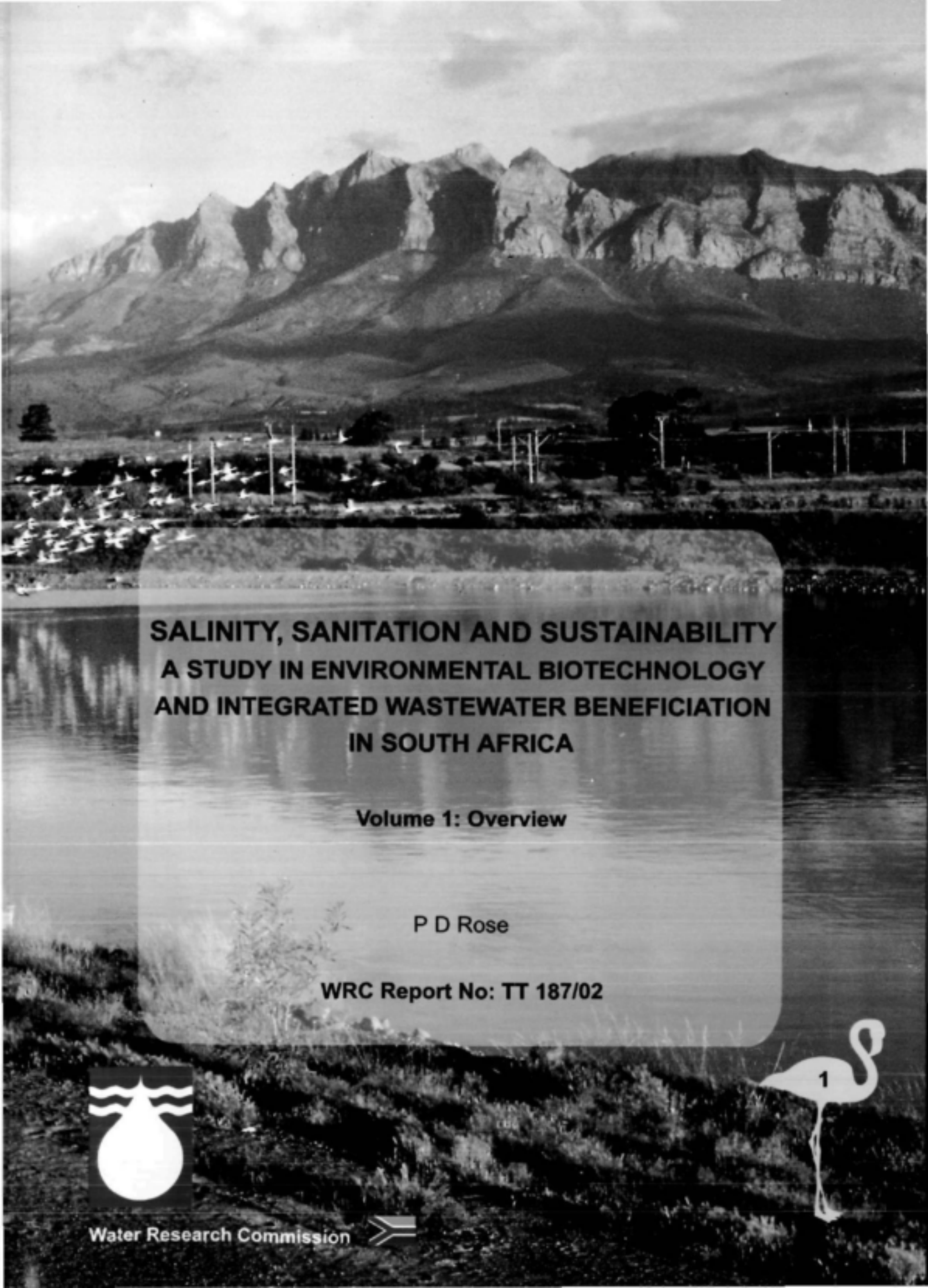

SALINITY, SANITATION AND SUSTAINABILITY
A STUDY IN ENVIRONMENTAL BIOTECHNOLOGY AND INTEGRATED WASTEWATER BENEFICIATION IN SOUTH AFRICA

Volume 1: Overview

P D Rose

WRC Report No: TT 187/02

1

Water Research Commission

REPORTS IN THE WATER RESEARCH COMMISSION PROJECT SERIES

SALINITY, SANITATION and SUSTAINABILITY

1 **Report 1**: Volume 1 - Overview

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Part 1: Meso-Saline Wastewaters The *Spirulina* Model.

3 **Report 3**: Volume 2 - Integrated Algal Ponding Systems and the Treatment of Saline Wastewaters

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11 **Report 11**: Volume 4 - The Rhodes BioSURE Process ®

Part 3: Sulphur Production and Metal Removal Unit Operations

12 **Report 12**: Volume 4 - The Rhodes BioSURE Process ®

Part 4: Treatment and Disposal of Sewage Sludges

Cover Photograph:

Flamingoes on tannery wastewater ponds at Mossop Western Leathers Co., Wellington, South Africa. The presence of Phoenicopteridae, including both the Greater and Lesser Flamingo, is an important indicator of healthy and naturally functioning saline aquatic ecosystems. This flock occupied the ponding system shortly after commissioning the novel *Spirulina*-based Integrated Algal Ponding System which had been developed for the treatment of tannery wastewaters. This apparent seal of environmental approval became an icon for the studies which followed in this series.

Photograph by Roger Rowswell, whose observation of this system, over a number of years, was instrumental in the initiation of these studies.

SALINITY, SANITATION AND SUSTAINABILITY

A STUDY IN ENVIRONMENTAL BIOTECHNOLOGY AND INTEGRATED WASTEWATER BENEFICIATION IN SOUTH AFRICA

Volume 1. Overview

A Report to the Water Research Commission
By

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Grahamstown

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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.

Ronnie Kasrils

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 have 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 a sustainable 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, and this was the methodology followed in these studies.

The principal aim of this programme was thus to investigate and develop technological enablement for linkages in 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 bio-process 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 an environmental seal of approval of the appearance of a large flock of flamingoes, which took up residence on the tannery wastewater ponds in Wellington, 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 development of the Rhodes BioSURE Process®, which links treatment of sulphate saline and sewage wastewaters.

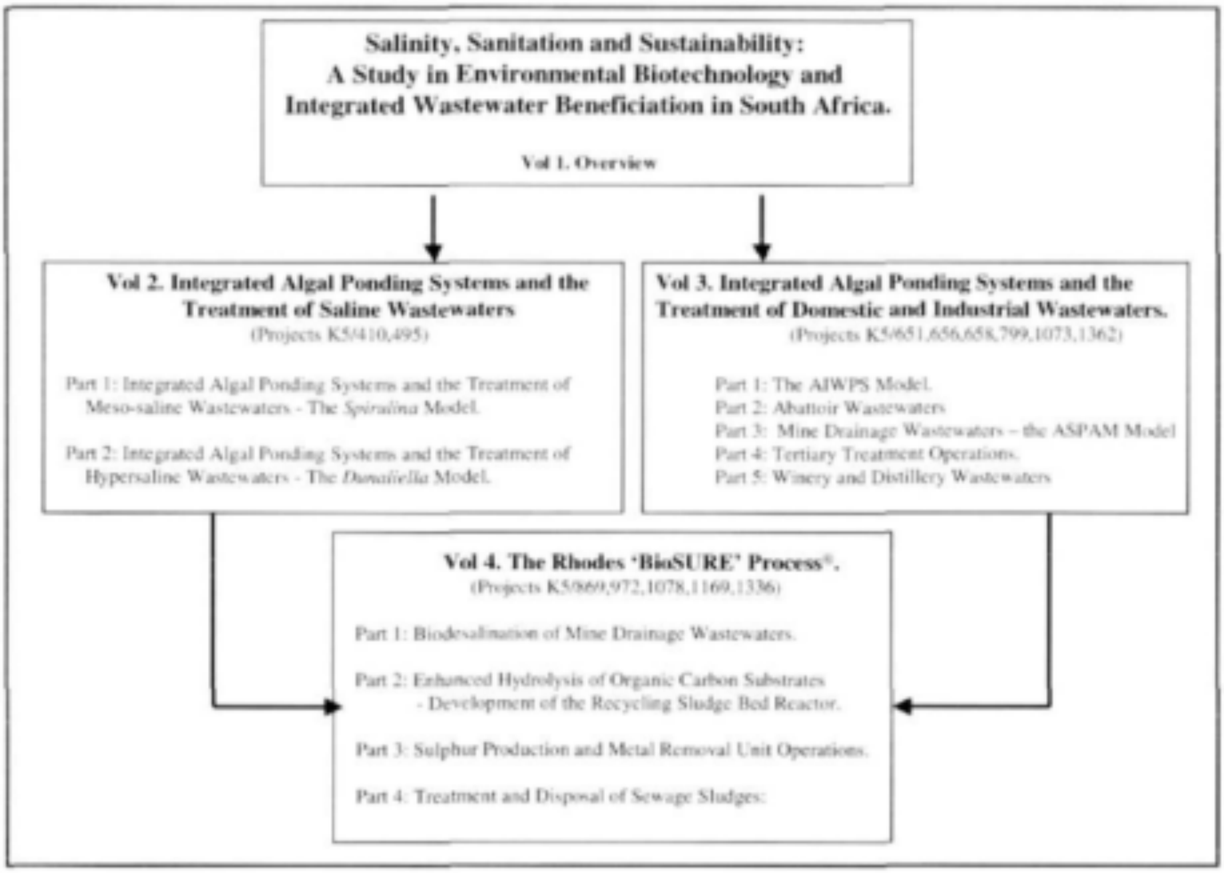

Figure P1. Research projects undertaken as components of the Water Research Commission study 'Salinity, Sanitation and Sustainability'.

A large number of people have assisted generously in many ways in the development of these studies, and are thanked individually 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
Rhodes University
Grahamstown

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EXECUTIVE SUMMARY

1 INTRODUCTION

Pollution and waste have been identified as critical issues undermining the sustainable development project in Southern Africa. The White Paper on Integrated Pollution and Waste Management (DEAT, 2000), confirming numerous previous studies, has targeted salinity and sanitation as severely impacting six of the seven priority pollution issues facing the region. The National State of the Environment Report (DEAT, 1999), undertaken in compliance with Agenda 21 (Rio Declaration on Environment and Development; UN, 1992), has noted the serious impacts of salinity on the environment, and also of sanitation (including broadly the provision of drinking-water supply and waste disposal services), as substantially affecting both the bio-physical environment and human development. A creeping salinisation of the public water system has advanced markedly since the1960s, with most major rivers in South Africa now seriously affected (Walmsley *et al.*, 1999). The African Ministerial Statement to the 2002 Johannesburg World Summit on Sustainable Development, has noted that implementation of sustainable development depends on addressing the causes of ill-health including "endemic, parasitic and infectious diseases which have retarded the quality and productivity of Africa's human resources. Many have roots in environmental conditions under which people live, in poor environmental hygiene, inadequate access to resources, such as water and sanitation, and inadequate nutrition" (UN, 2001a).

This report describes a twelve-year Water Research Commission (WRC) study, commencing 1990, which has investigated an environmental biotechnology approach in the feasibility of integrating management of the saline and sanitation wastewater systems. This was an investigation of enabling technologies, and was based on studies in saline biotechnology which had been initiated in the mid-1980s in the Environmental Biotechnology Group (EBG) at Rhodes University. The objectives of this programme had been informed and shaped within the climate of the sustainability idea, emerging around the time of the 1987 World Commission on Environment and Development (WCED, 1987), and in the period leading up to the United Nations Conference on Environment and Development in Rio de Janiero (UN, 1992).

In one of the early landmark contributions to operationalising the sustainability concept, Heaton *et al.* (1991) had argued that reconciling the economic and environmental goals societies had set for themselves would be possible only through a revolutionary transformation in technology – a shift to new technologies that dramatically reduce environmental impact per unit of prosperity. It was necessary that technologies not only transform human activities into resource-light consumption patterns, but in terms of non-renewable resource depletion, new technology is required to enable societies to live strictly off nature's income, rather than consuming its capital (Speth, 1990). Jansen (1997) has noted that the broad goal of achieving sustainability over the long-term requires the fundamental renewal of the whole means by which human needs are fulfilled. A broad focus of innovation has thus fallen on efforts to achieve a 'closed systems' approach to sustainability whereby human activities, and the associated technological environment, are detached as far as possible from the bio-physical environment related to natural systems.

In meeting objectives on non-renewable resource depletion the boundary between wastes and resources may be taken as arbitrary, with a utility cost determining the status of waste or resource. Hacking (1986) had noted that wastes presented something of a golden opportunity to biotechnology, and waste recovery, recycle and reuse have become issues of major attention. Thus waste beneficiation, conceived as operations that add value by transforming materials from a raw-material status into finished products, has been identified as an important incentive in shifting the delivery of sustainability targets, from regulatory and coercive modes, to market-driven implementation (Rose, 1991). Where communities may derive a livelihood from the long-term waste beneficiation operation, the fusion of social, environmental and economic objectives contribute to meeting sustainable development goals.

2 THE WRC STUDY

The Rhodes EBG was appointed by the WRC, in 1990, to undertake a one-year feasibility study to evaluate the research potential of environmental biotechnology in developing waste beneficiation approaches to the treatment and management of saline and sanitation wastewaters. In addition to exploring the principles of value recovery from these wastes, the project was to examine opportunities for integration in the management of these systems. The Project K5/410 – 'A biotechnological approach to the removal of organics from saline effluents' – undertook an assessment of the broad technological implications of Algal Ponding Systems as a 'core technology' to effect an integrated management of the saline and sanitation systems, and was to make recommendations on the merits of a longer-term Research and Development (R&D) investment in this area of technology development.

This initiative sought to evaluate novel approaches in waste management and treatment emerging in the rapidly developing field of environmental biotechnology, and to link this to the capture of nutrient values, and waste stream beneficiation potential, available in applications of algal biotechnology. Evaluation of aquatic photosynthetic production in the micro-algae had developed rapidly in the 1970s and 1980s and, given photosynthesis as the most abundant energy-storing process on earth, the use of algal systems in industrial production of speciality biomass and high-value fine chemical products, was identified as offering opportunities to develop long-term waste beneficiation and sustainability objectives.

The recommendations of the initial study were followed up in a series of 12 projects, undertaken by the EBG with WRC, and joint WRC/Industry involvement, over the subsequent period. This report provides an overview of the R&D output associated with this undertaking, and the detailed findings are documented in a number of individual reports which are published separately (Appendix 1).

The principal focus of these studies was underwritten by the following assumptions and objectives:

- ❑ The 'closed system' objective requires that saline concentrates should be kept outside the public water system where at all possible, and disposal of saline wastes by dilution should be phased out where alternatives become available. Technology development should focus on enabling this objective;

- The beneficiation potential of saline wastes should be explored to contribute to 'integrated wastewater resource management' objectives and provide cost-benefit incentives in their management, to achieve a basis for their long-term sustainability. The production opportunities in saline micro-algal systems would contribute to this objective;
- Useful linkages between the saline and sanitation systems should be explored in order to relieve pressure on stressed fresh water systems. These might include the reticulation of water-borne sewage in saline wastewaters, and the use of saline wastewaters for the co-disposal of sewage sludges and other organic wastes;
- The pervasive sulphate-saline wastewater problem, widely generated in both gold and coal mining, and in other industrial activities, provides a useful model for studying such potential linkages in the saline and sanitation systems.

In dealing with these issues a number of questions would have to be addressed including:

- Could an investigation of linkages in the saline and sanitation wastewater systems provide a useful model for studying problems in 'integrated waste resource' and 'closed systems' management?
- What are the technical feasibility and constraints of such proposed linkages?
- Could algal ponding systems be appropriately adapted as environmental-scale bioreactors providing an upgradeable 'core technology' with wide potential application in the treatment of both saline and sanitation wastewaters?
- In addition to low-cost sustainable water treatment technology, could Integrated Algal Ponding Systems (IAPS) and production of high-value algal biotechnology products be linked for the recovery of nutrient values in these systems?
- Could the provision of value-adding beneficiation of saline and sanitation wastes, in the form of bio-products and treated water, provide economic incentives and job creation, where a fusion of long-term economic, environmental and social objectives would provide a basis for achieving sustainable development targets?

3 IAPS – A 'CORE TECHNOLOGY'

Recommendations on IAPS applications made in the initial feasibility study (Project K5/410) were followed up in a five-year project with the same title (Project K5/495 'A biotechnological approach to the removal of organics from saline effluents'). It was evident from these initial studies that the development of 'closed system' and 'integrated wastewater resource management' applications in salinity and sanitation, based on a process of environmental and algal biotechnology-driven innovation, was dependent on the development of an indigenous capacity with respect to the engineering requirements for the design, construction and operation of IAPS. Best studied at this time was the trade-marked Advanced Integrated Wastewater Ponding Systems (AIWPS), developed for domestic sewage treatment by William Oswald at the University of California, Berkley, USA.

Following a visit to California by the author in 1990, and later by Dr Oliver Hart, Research Manager at the WRC, and a return visit to South Africa by Professor Oswald in 1992, the WRC Project K5/651, "Appropriate low-cost sewage treatment using the advanced algal high rate oxidation pond", was undertaken to effect a technology transfer exercise in which an IAPS demonstration and research plant would be constructed at the Rhodes University

Environmental Biotechnology Experimental Field Station in Grahamstown (Figure 1). This project commenced in 1994 and the plant and Experimental Field Station were officially opened in April 1997 by Professor Kader Asmal, Minister of Water Affairs and Forestry.

Figure 1. The Rhodes University Environmental Biotechnology Experimental Field Station at the Grahamstown Disposal Works showing the Integrated Algal Ponding System demonstration and research plant and laboratories.

Process monitoring studies were undertaken over the following five years in follow-up Project K5/799: 'Development and monitoring of integrated algal high rate oxidation pond technology for low-cost treatment of sewage and industrial effluents'.

This technology transfer initiative provided the engineering base for a range of application studies on IAPS in saline and sanitation wastewater treatment, and the potential linkage of these systems in an 'integrated wastewater resource management' approach to the problem. These studies were focussed in five main areas of application:

- The biotechnology of meso-saline wastewater treatment – the *Spirulina* model;
- The biotechnology of hyper-saline wastewater treatment – the *Dunaliella* model;
- The biotechnology of sulphate-saline wastewater treatment – the development of the ASPAM and Rhodes BioSURE Processes®;
- The biotechnology of sewage sludge disposal – linkage of sewage and sulphate-saline wastewater treatment;
- The development of the IAPS application as an upgradeable 'core technology' in saline, domestic and industrial wastewater treatment.

These studies formed the subject of 12 follow-up projects over the study period, and the relationship between these studies is detailed in Figure 2.

This report provides an overview of the WRC study, 'Salinity, Sanitation and Sustainability', and summarises the principal findings which emerged in each of the individual projects. Each project will also be the subject of an independent report (Appendix 1).

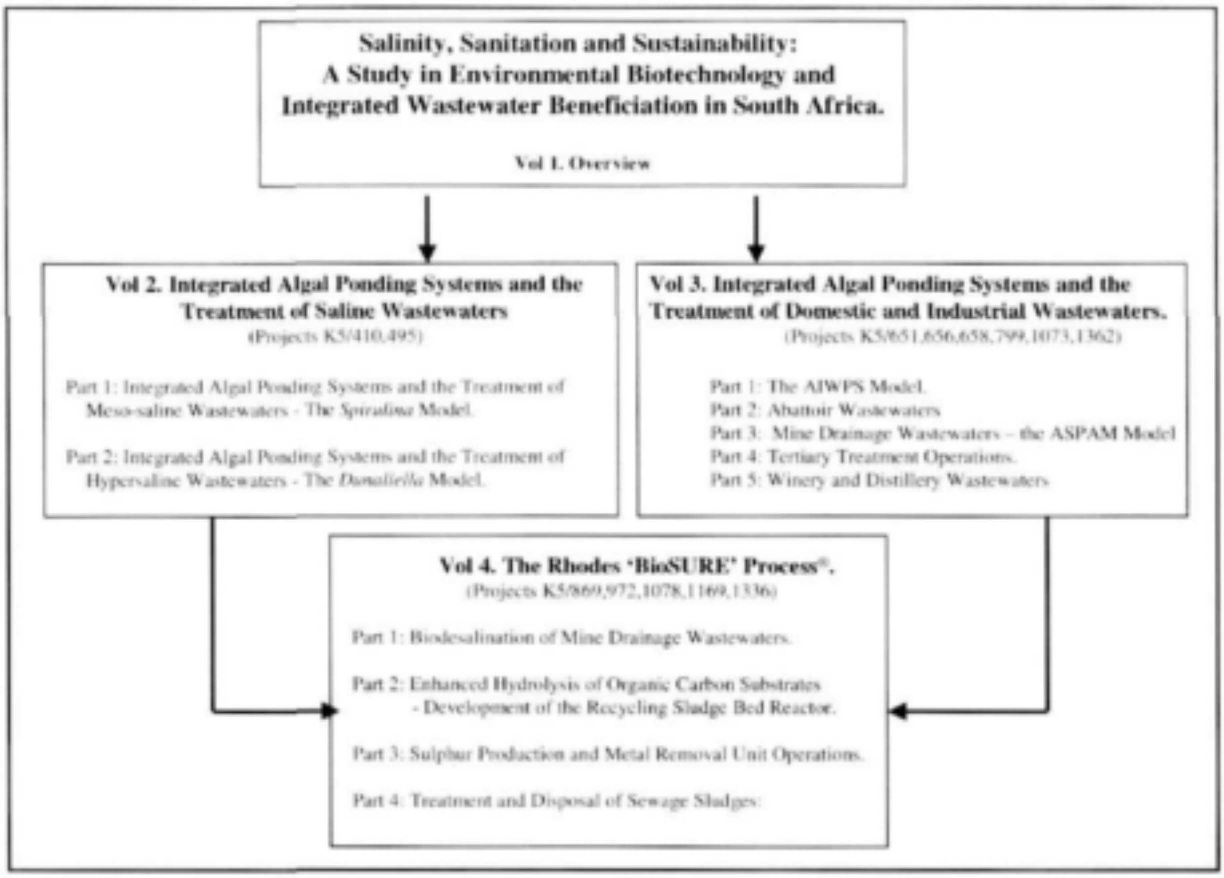

Figure 2. Research projects undertaken as components of the Water Research Commission study in 'Salinity, Sanitation and Sustainability' – an investigation of integration in wastewater beneficiation in South Africa.

4 MESO-SALINE WASTEWATERS

Brackish and meso-saline wastewaters (< 40g.L^{-1} total dissolved inorganic solids – TDIS), occur widely in South Africa due to both natural causes and anthropogenic activity. Industrial and agricultural saline wastes, in particular, may also be quite heavily contaminated with organic compounds, heavy metals and nutrients. The tannery Waste Stabilisation Pond (WSP) was chosen as a model environmental-scale bioreactor system in the K5/495 study of organic saline wastewater treatment for a number of reasons:

- ❑ The use of WSP is well-established technology for the treatment and disposal of high COD loads in fresh (non-saline) wastewaters;
- ❑ In addition to high COD loads, tannery effluents contain a range of components including heavy metals and high levels of sulphate, ammonia, nitrates and protein nitrogen. This provides, in some sense, a worst-case scenario of what may be encountered in saline wastewater impoundments used to isolate salinity from the public water system;
- ❑ A wide salinity concentration gradient, from meso- to hyper-saline conditions, occurs across the evaporation cascades in saline wastewater impoundments, providing the sequential dominance of a range of different microalgal and cyanobacterial species in near mono-species cultures;
- ❑ The engineering design of WSP is well established, particularly in the treatment of large wastewater volume flows, which provides a useful model for evaluating their

application as appropriate bioreactors for the treatment of saline wastewater streams, such as mine drainage wastewaters;

- The low-cost, and quasi-passive nature of WSP, makes for sustainability where the treatment requirement for wastewaters flows is anticipated to stretch over long periods of time (e.g. mine drainage wastewater), and where impoundment may present the only option for protecting the fresh water resource, particularly in the context of the developing world.

Following a detailed study of the microbial ecology of the saline WSP at Mossop Western Leathers Co. in Wellington, South Africa, the dominance of *Spirulina* sp. and *Dunaliella* spp. at different stages of the increasing salinity gradient in the evaporation ponding cascade was described. This led to the development of a *Spirulina*-HRAP (S-HRAP) for tannery effluent treatment, through laboratory and pilot plant studies, to the construction of a full-scale industrial unit at the Mossop-Western Leathers tannery (Figure 3).

Figure 3. Paddle wheel of the industrial-scale 2500 m^2 *Spirulina*-HRAP constructed in Wellington, South Africa, for the treatment of tannery wastewaters.

The application of the S-HRAP as a component unit in an IAPS treatment operation, but also as a freestanding unit operation for upgrading the established and malfunctioning WSP was demonstrated. Appropriate loading rates were determined and it was shown that a high quality effluent may be produced in the system. In addition to effective odour control by algal capping of the ponds, a notorious problem in these systems, the production of a feed-grade quality *Spirulina* biomass was also developed as a by-product of the treatment process. Nutritional and toxicological testing demonstrated successful use of the harvested biomass in aquaculture and stock ration applications, and was incorporated into the novel 'Abfeed' for artificial culture of the South African abalone *Haliotis midae*, developed by the Rhodes University Ichthyology Department. The commercial production and marketing of *Spirulina* biomass produced in this ponding system has commenced as a spin-off enterprise.

The industrial-scale IAPS plant was officially opened in Wellington by the Minister of Water Affairs and Forestry, Prof Kader Asmal, on 28 November, 1997. These studies are reported in WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Saline Wastewaters. Part1: Meso-saline Wastewaters – The *Spirulina* Model'.

5 HYPER-SALINE WASTEWATERS

Hyper-saline wastewaters (>40mg.L^{-1}TDIS) are produced in most desalination operations, and the environmental fate of these concentrates presents the single most important issue in their final disposal. The use of these wastes for the large-scale production of halophilic microalgae provides potential for the production of a wide range of speciality fine chemical products.

Prolific growth of the halophilic green alga *Dunaliella salina* was observed in the hyper-saline regions of the tannery WSP cascade, and the ecology of these blooms was also investigated in the K5/495 study. Laboratory studies on factors regulating cell growth and the hyper-accumulation of β-carotene in this organism in the organic saline environment, led to the development and piloting of a free-standing *Dunaliella*-HRAP (D-HRAP) for the treatment and removal of organic wastes in hyper-saline wastewaters. This, together with heavy metal removal, is important where wildlife refuges and recreational areas develop around such impoundments.

Follow-up studies on the use of the D-HRAP for the treatment of organic contamination in hyper-saline wastewaters was investigated further at the Botswana Ash Co., Sua Pan, Botswana, where soda ash is produced as a solar evaporite. The pilot D-HRAP constructed and operated at Sua Pan is shown in Figure 4.

Figure 4. The pilot-scale *Dunaliella*-HRAP developed for the treatment of organic contamination in saline carbonate brines at the Botswana Ash Co. Sua Pan, Botswana.

Fundamental studies on stress induction and response mechanisms in *Dunaliella salina* demonstrated that the process of the hyper-accumulation of β-carotene by this organism may be successfully manipulated by the separation of active and stationary phases of growth. This work resulted in the development of the WRC- patented Dual Stage Process for the commercial production of β-carotene as a high-value speciality chemical product. The process was scaled up in an EBG/Sasol collaboration at Rhodes and at Sastech in Sasolburg. This was followed up in a technical-scale plant constructed in Uppington, South Africa. Production studies and economic analysis has shown that the Dual Stage Process, as a cost-effective method for biological β-carotene production, offers substantial yield and production cost advantages. A high market value for β-carotene as pro-vitamin A, food colourant and anti-oxidant, provides a potential basis for economic sustainability in the hyper-saline wastewater treatment operation.

These studies are reported in WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Saline Organic Wastewaters. Part 2: Hyper-saline Wastewaters – The *Dunaliella* Model'.

6 SULPHATE-SALINE WASTEWATERS

During the tannery WSP studies, an unexpected observation of enhanced hydrolysis and breakdown of particulate organic matter was made in the anaerobic sulphate reducing compartments of these ponding systems. The accumulation of solids is a particularly refractory problem in tannery ponds, and the Wellington IAPS had been successfully retrofitted by incorporating these observations and optimising sulphate reducing bacterial (SRB) activity in the primary facultative pond. This enabled effective precipitation of metal sulphide complexes, and the elimination of potential heavy metal contamination in the micro-algal biomass produced in the subsequent S-HRAP unit process.

Fundamental studies were then undertaken in the mechanisms underpinning the enhanced hydrolysis and solubilisation reactions which had been observed, and in which complex organic carbon wastes might be efficiently solubilised and mobilised as electron donor sources for sulphate reduction activity. In addition to explaining aspects of basic processes of nutrient cycling in sulphidogenic aquatic systems, it was shown that the mechanisms involved might also be engineered to effect the co-disposal of a range of complex organic carbon wastes, such as primary sewage sludge, together with the treatment of high-sulphate wastewaters.

Previous work on the engineering of sulphate reducing bioprocesses had concentrated on high-cost electron donor substrates such as ethanol. The development of waste carbon as an electron donor source appeared to offer potential cost advantages, especially for treatment of large volume flows of sulphate-saline wastewaters, that would be sustainable over the long periods of time over which this treatment may be anticipated.

At the same time observations of stable sulphur biofilm formation due to sulphide oxidation on the surface of tannery ponds led to studies in the microbial ecology of these structures. This was followed up by a sulphur recovery bioprocess development study which targeted linearisation of the biosulphur cycle and an effective biodesalination of sulphate-saline wastewaters.

These findings in complex carbon substrate utilisation and sulphur recovery facilitated process development studies in a number of applications including the treatment of sulphate-saline wastewaters and disposal of organic wastes.

6.1 The ASPAM Process

The widespread application of biosulphidogenic processes for the treatment of high sulphate wastewaters, including acid mine drainage (AMD), has been largely constrained by the availability of low-cost carbon and electron donor sources for SRB activity, and the size and cost of bioreactors required for large-volume wastewater treatment operations. The demonstration of tannery ponding systems, as appropriate environmental-scale bioreactors for large-volume sulphate wastewater treatment, and the enhanced hydrolysis of complex organic carbon substrates appeared to offer a useful mechanism for linking the saline and sanitation systems. This led to the development of the Integrated Algal Sulphate Reducing Ponding Process for Acidic and Metal Wastewater Treatment (ASPAM). The process flow diagram is shown in Figure 5.

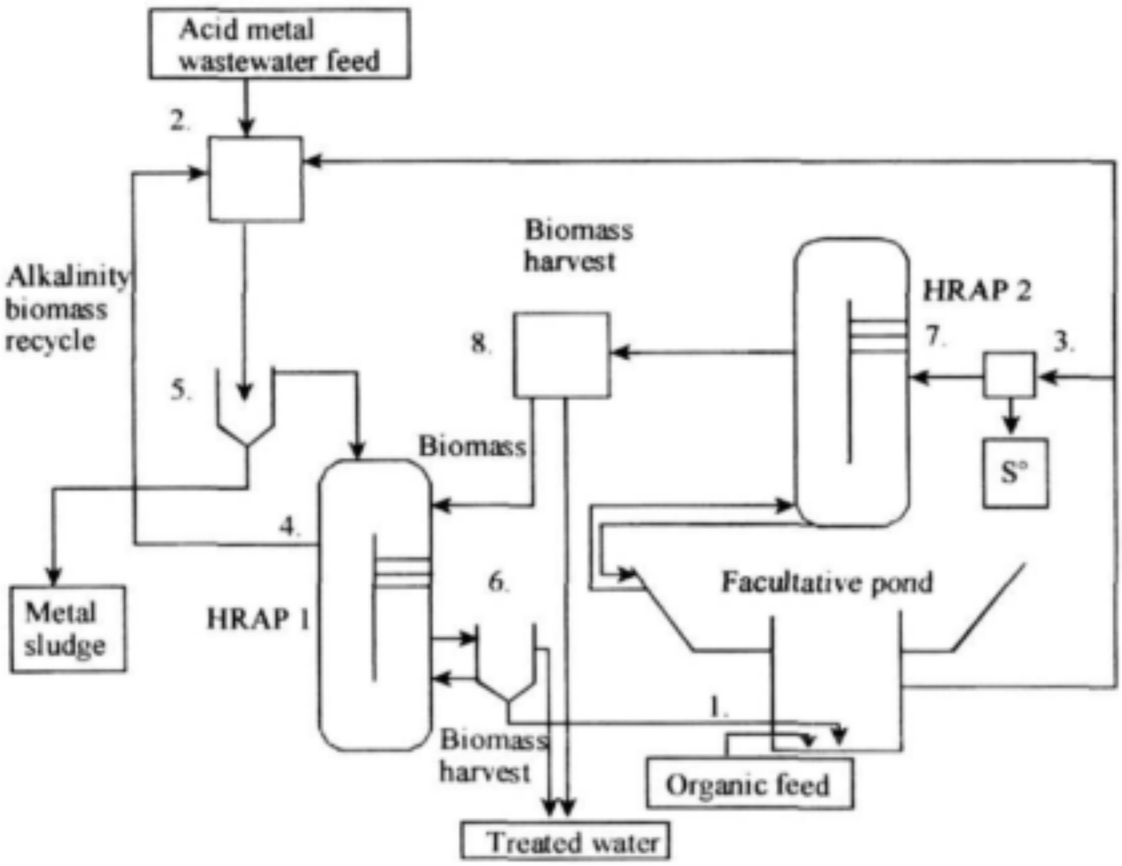

Figure 5. Flow diagram of the individual unit operations of the Integrated Algal Sulphate Reducing Ponding Process for Acid Metal Wastewater Treatment (ASPAM). Organic feed enters at 1 = Facultative pond with anaerobic upflow digester compartment; Feed water enters at 2 = Inlet and metal precipitation unit; Sulphide is recycled to metal precipitation unit from 3 = sulphide recycle and sulphur recovery unit; Alkalinity and algal biomass generated in High Rate Algal Pond (HRAP)1 recirculated via 4; 5 = Metal sludge settler; 6 = Algal biomass settler; 7 = High Rate Algal Pond (HRAP)2 for capping the Facultative Pond and seeding HRAP 1 with fresh biomass; 8 = Algal biomass harvester.

The system incorporates various aspects of IAPS to achieve sulphate reduction using a range of waste carbon sources including algal biomass grown in the process. Heavy metal removal and acid neutralisation reactions involve the recycle of sulphide from the

Facultative Pond, with photosynthetically generated alkalinity and algal metals adsorption contributing to the final treatment of the water. In addition to acid and heavy metal removal, a biodesalination of the AMD is effected with the removal of sulphide from the system. Individual unit operations of the process have been studied and optimised, and the scale-up evaluation of the process at pilot-scale is now pending. The results of this study are reported in WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 3: Mine Drainage Wastewaters – The ASPAM Model'.

Investigation of the linkage of sewage sludge disposal and the treatment of AMD wastewaters was undertaken in a number of closely related WRC projects; Project K5/656: 'Appropriate low-cost treatment of sewage reticulated in saline water using the algal high rate oxidation ponding system'; Project K5/869: 'Biological sulphate desalination and heavy metal precipitation in industrial and mining effluents using the IAPS'; 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'; 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'.

These studies which resulted in the development of the Rhodes BioSURE Process® have been reported in WRC Report: 'The Rhodes BioSURE Process®. Part 1: Biodesalination of Mine Drainage Wastewaters'.

The development of the sulphur recovery unit, which provides for the final biodesalination operation by linearising the sulphur cycle, was undertaken in separate project studies which are noted below.

6.2 The Rhodes BioSURE Process®

At the same time as the development of the extensive ASPAM system was being undertaken, process development studies commenced in the EBG to optimise the enhanced hydrolysis reaction within a separate unit operation, which might be subjected to more stringent engineering control than possible in the Facultative Pond. This study led to the development of the Recycling Sludge Bed Reactor, and it was shown that in this unit PSS as carbon source may be solubilised biosulphidogenically to yield a hydrolysed product of over 30% volatile fatty acid equivalents. This hydrolysate may in turn be fed as the electron donor source to a subsequent reactor where sulphate reduction is optimised. Sulphur recovery, metal precipitation and final polishing make up the unit operations of the Rhodes BioSURE Process® shown in Figure 6.

While process scale-up had been planned to commence at the East Rand Water Care Company (Erwat) sewage works in Nigel during 1997, the so-called Grootvlei environmental-incident intervened. The increased pumping and dewatering into the Blesbokspruit, by the Grootvlei Gold Mine near Springs, South Africa, and the resulting pollution impacts had developed into a political issue of potentially international significance. AMD pollution from the mine dewatering exercise threatened the Marievale and Daggafontein Bird Sanctuaries – Wetlands of International Significance under the Ramsar Convention, to which South Africa is signatory. Following a pump shutdown order by the Ministry of Water Affairs and Forestry, in 1996, a technology evaluation exercise was agreed as a prerequisite for the resumption of pumping, and which would undertake the comparison of a range of options available to deal with the mine dewatering problem. The Rhodes EBG was invited late in 1997 to participate in this exercise, and to undertake the BioSURE® pilot studies on-site at Grootvlei Mine.

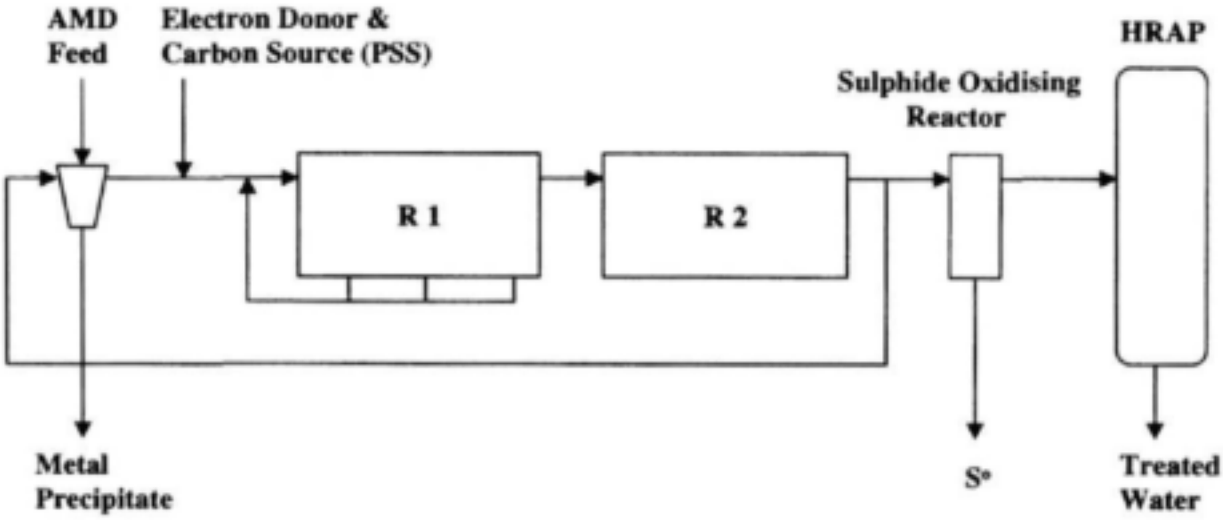

Figure 6. Process flow diagram of the Rhodes BioSURE Process® applied to the treatment of acid mine drainage wastewater (AMD). R1 = Recycling Sludge Bed Reactor (RSBR); R2 = secondary (baffle) reactor; HRAP = high rate algal pond; PSS = primary sewage sludge. A side stream of sulphide-rich wastewater is blended with incoming minewater to precipitate contaminating heavy metals. The sewage sludge carbon source is added to the metal-free stream which passes to the RSBR, where hydrolysis of particulates and some sulphate reduction occurs. The dissolved organic stream passes to a secondary reactor where it is used as the feedstock in the final sulphate reduction step. The treated water is then discharged via a Sulphide Oxidising Reactor to an HRAP polishing stage. Treated water, sulphur and algal biomass are produced as final products.

The BioSURE® pilot plant was constructed in Gahamstown and then located to site at Grootvlei Mine No 3 Shaft in January 1998, where it was operated for 18 months, using primary sewage sludge supplied by Erwat as the carbon source (Figure 7). A sulphate removal around 80% was achieved under steady state operating conditions, and the production of a metal-free and non-infectious polished final water from the HRAP was demonstrated, with sulphate levels reduced from around 2000 $mg.L^{-1}$ to 350 -400 $mg.L^{-1}$.

6.3 Coal Mine Wastewater and Passive Systems Treatment

Industry participation in a number of follow-up development studies of the BioSURE Process® applications in coal mine wastewater treatment has also been undertaken. An Eskom study has investigated the use of the BioSURE Process® for linking long-term decanting coal mine wastewaters in an 'integrated wastewater resource management' programme known as the Eskom Sustainable Development Project, which has been described below.

The use of lignocellulosic wastes, as an alternative complex carbon and electron donor source for sulphate reduction, has been investigated in a Department of Arts Culture, Science and Technology Innovation Fund project on the development of Passive Systems for AMD treatment. Passive Systems, involving no external energy input and minimum

Figure 7. The Rhodes BioSURE® pilot plant located at Grootvlei Mine, Gauteng Province, and using primary sewage sludge as the carbon source in the treatment of acid mine drainage wastewaters.

maintenance, will play an important role in achieving final mine closure certification, especially where regulatory authorities are faced with long-term commitments and ongoing mine drainage wastewater production. Sulphate removing Passive Systems have not been successfully implemented elsewhere.

7. SULPHATE-SALINITY AND ORGANIC WASTE DISPOSAL

While the use of primary sewage sludge as a carbon source for sulphate reduction in AMD treatment formed the principle focus of the above BioSURE Process® studies, it was apparent from the outset that the availability of a high-sulphate source might also be used where the disposal of sewage sludges would be the principal objective. The Recycling Sludge Bed Reactor would remain the core unit operation in the process with alteration in the COD:sulphate ratio determining whether sulphide reduction or solids disposal was the principal target.

This application of the BioSURE Process® in organic waste disposal has been investigated in association with Erwat in Project K5/1169: 'Intermediate scale-up evaluation of the Rhodes Process for hydrolysis and solubilisation of sewage sludges in a sulphate reducing bacterial system'. In preliminary studies it was shown that, in addition to the enhanced solubilisation of solids and an effective precipitation and removal of heavy metals, the elimination of infectious agents is also achieved in the sludge solubilisation process. The solubilised sludge solids are then passed to down-stream treatments, such as biological filtration or activated sludge and, in addition to a substantial sludge volume reduction, the production of a non-hazardous humus sludge is generated as the final product of the process. Sulphide may be recovered via a sulphide oxidation process (described below) and recycled, and thus maintaining a sulphate inventory within the system where a constant external supply is not readily available.

A technical-scale plant has been constructed at the Ewat Ancor Works in Springs, involving the scale-up of the Recycling Sludge Bed Reactor in a 2 ML unit (Figure 8), and which draws its sulphate stream in a pipeline which has been laid from the nearby Grootvlei Mine. Results will be reported in WRC Report: 'The Rhodes BioSURE Process®'. Part 4: Treatment and Disposal of Sewage Sludges'.

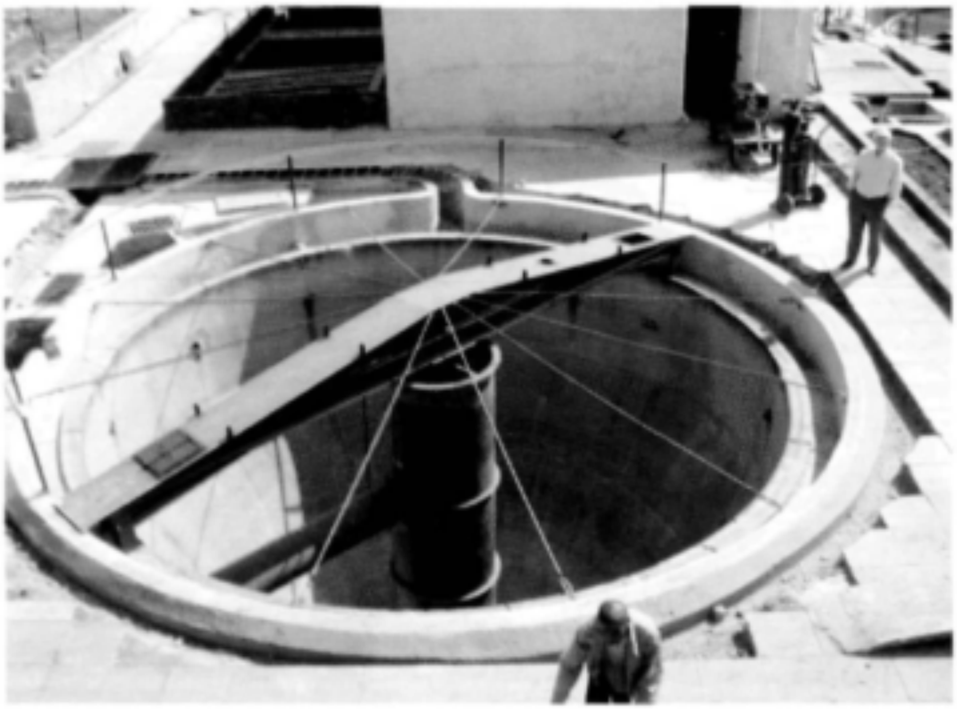

Figure 8. The scaled-up 2 ML Recycling Sludge Bed Reactor in the BioSURE® sewage sludge solubilisation technical-scale plant constructed at Erwat's Ancor Works in Springs. Surface struts provide support for a covering membrane.

8. BIODESALINATION AND SULPHUR RECOVERY

The final removal of sulphur in one form or another is necessary to effect the linearisation of the biological sulphur cycle, and thereby the biodesalination of the treated sulphate-saline wastewater. Where sulphidogenesis provides the initial step in the biodesalination operation, sulphide may be removed in a number of ways, including its oxidation to elemental sulphur (S^0). Following the final precipitation and removal of S^0 from the treated stream, this may serve as a value-added end-product of the waste treatment operation.

However, where a sulphate inventory is required in waste organic carbon solubilisation and disposal operation, such as sewage sludge disposal (i.e. where an unlimited sulphate source may not be available), the S^0 might be fully oxidised to sulphate and returned to the sulphate reduction process.

The formation of floating sulphur biofilms has been observed at the air/water interface in sulphidogenic water bodies under specific conditions. These were observed in the tannery ponding system studied, and investigation of the microbial ecology of sulphur biofilm formation was undertaken by the EBG. These studies not only resulted in an explanatory model describing the microbiology of their formation, but also in the development of a number of Sulphide Oxidising Bioreactor configurations which have been evaluated at pilot-scale at the EBG Experimental Field Station in Grahamstown.

The scale-up development of the Sulphide Oxidising Bioreactor has been undertaken in WRC Project K5/1336 'Scale-up development of the Rhodes BioSURE Process® for sewage sludge solubilisation and disposal'. Industrial scale-up application of this development has also been undertaken in the Department of Arts Culture Science and Technology Innovation Fund Project on passive minewater treatment systems, and in the Erwat project on sewage sludge disposal. The results of this study are reported in WRC Report, 'The Rhodes BioSURE Process®. Part 3: Sulphur Production and Metal Removal Unit Operations'.

9 DEVELOPMENT AND ENGINEERING OF IAPS PROCESS APPLICATIONS

In demonstrating a role for IAPS in the linkage of the saline and sanitation systems, their development as a 'core technology' was undertaken for 'fresh' wastewaters, as well as for the saline organic wastewater applications described above. In addition to the low-cost domestic sewage treatment application, the requirement of an 'upgradeability' factor has also been noted in the social development context. Water treatment systems should be able to flexibly handle increased volume flows, as well as industrial production effluents, as communities develop from subsistence levels of enterprise.

Following the construction of the IAPS demonstration and research plant for domestic sewage treatment in Grahamstown, it was operated and monitored over a five year period and will be reported as WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part1: The AIWPS Model'. During this time, process development studies were also undertaken to adapt the process to local conditions including an investigation of the use of the HRAP as an independent unit operation, the Independent HRAP (I-HRAP), for nutrient removal. Effective phosphate and nitrate removal was demonstrated, and it was shown that the I-HRAP might be incorporated within an IAPS configuration, or as a free-standing unit operation added on to an existing works, where the general standard for surface water discharge could not be met. These conditions are common in the small treatment works. The results of the study are reported in WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 4: System Performance and Tertiary Treatment Operations'.

In addition to the tannery wastewater system a number of other industrial applications of IAPS were investigated in extending the use of the technology and testing its potential upgradeability. This included the construction of a pilot plant for the treatment of abattoir wastewaters in collaboration with Abakor (WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 2: Abattoir Wastewaters'. The treatment of winery and saline distillery and wine lees wastewaters was undertaken in collaboration with Brennokem Co. in Worcester, South Africa. The pilot plant used in this study is shown in Figure 9 and the results have been reported in WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 5: Winery and Distillery Wastewaters'.

Figure 9. Integrated algal ponding system pilot plant constructed at the Brennokem Co. wine lees plant in Worcester, South Africa, for the treatment of winery, and saline distillery and wine lees wastewaters.

A study of the use of saline wastewaters for the reticulation of water-borne sewage, as a means of relieving pressure on stressed fresh water systems, commenced in 1996 as laboratory studies in Project K5/656, 'Appropriate low-cost treatment of sewage reticulated in saline water using the algal high rate oxidation ponding system'. Apart from the low-cost advantages of the IAPS application, algal oxygenation would present certain advantages over mechanical systems, given reduced oxygen solubility in saline solutions. Process application studies were planned in a Northern Cape area where large volumes of sodium chloride saline waters were available, and results from the tannery system had already indicated that the saline IAPS could be expected to cope with higher organic loads than might be anticipated in the domestic wastewater application.

However, this study was postponed with the commencement of the Grootvlei investigation, and has as yet not been resumed. In the interim, dual pipeline reticulation systems have been investigated in Australia and elsewhere (NDSP, 1999). Reestablishment of this study has been recommended as a sustainable development initiative.

10 CONCLUSIONS

Achieving sustainability in the saline and sanitation wastewater systems, critical pollution issues in the development context in Southern African and indeed much of the developing world, may be influenced by current developments in environmental biotechnology. In addition, the application of algal biotechnology as a subset, particularly as related to the WSP as an environmental-scale bioreactor, provides an upgradeable 'core technology' including waste beneficiation as an incentive for 'closed system' and 'integrated wastewater resource management' objectives. The WRC studies described here were undertaken as model systems for investigating feasibility in this general approach and, as a technology-push initiative, to possibly contribute to a wider investment in the sustainability project for salinity and sanitation.

In terms of these objectives the study has developed, or demonstrated an extension of, IAPS-related applications in a number of wastewater treatment processes. The following was shown:

- Saline and sulphate-saline wastewaters may be feasibly treated in algal ponding systems and, with the removal of organic and metal pollutants, may be rendered safe for segregation from the public water system in hyper-saline impoundments;
- In addition to providing increased environmental safety for saline wildlife refuge sites and recreational wetlands, algal production of speciality fine chemicals and biomass products may provide for a cost-effective sustainable beneficiation of these wastes;
- Nutrient values present in saline wastewaters may be recovered in the form of value-added algal by-products, and their return to both the economy, and the biological environment, provides enabling technologies for establishing 'integrated wastewater resource management' objectives in the management of these wastes;
- The IAPS concept has provided a technological base as a 'core technology' for bioprocess innovation in a number of related wastewater treatment applications. These include small community sanitation, and technological sustainability in terms of low-cost construction, the operational skills requirement, and 'upgradeability' to include increased wastewater volumes and the treatment of industrial wastewaters as communities develop economically. Industrial applications demonstrated include tannery, abattoir, winery and distillery, and acid mine drainage wastewaters;
- The co-disposal of sulphate-saline and domestic wastes in linked utility-based operations provides for organic waste disposal, for the long-term treatment of AMD following mine closure, and including other sulphate-enriched heavy metal-containing wastewaters;
- The feasibility of linkage in the saline and sanitation wastewater systems has been demonstrated, in certain specific applications, based on developments in environmental biotechnology, and may advance 'integrated wastewater resource management' and, ultimately, 'closed system' targets in achieving sustainable development in the Southern African Region.

Although fully optimised 'closed systems' production may lie somewhere in the future, attempts have commenced to achieve quite intricate integration of waste resource management operations. One of these is the Eskom Sustainable Development Project which has addressed the environmental problem of long-term decanting mine wastewaters and the development needs of local communities after mining operations cease. Achieving successful mine closure and final walk-away have become serious problems in the economics of mining operations. This integrated waste resource beneficiation operation (Figure 10), has investigated the use of the BioSURE Process® as the preliminary treatment operation removing sulphate and heavy metals. Reverse osmosis brines would pass to halophilic algal culture, and treated water via *Atriplex* (old man salt bush) hydroponics to stock and vegetable production, and aquaculture operations. Organic carbon wastes generated in the system, particularly from maize production and agro-forestry, would provide the electron donor sources for the sulphate reduction operation. Apart from production of treated water as a final product returned to the environment, the community responsible for the treatment of the mine drainage wastewater would in turn provide for themselves, over the long term, by the 'integrated waste resource management' operation. The fusion in this way of economic, environmental and social objectives would provide a sustainable development outcome to an otherwise intractable problem.

Clearly the economics of integration in such 'grand plan' systems are not trivial. While they depend in the first instance on technological enablement, and a 'technology-push' rather than a 'market-pull' approach to start with, this has been a common feature of much sustainability research at this early stage of its development. Jansen (1997) has noted that sustainable technology development, and the process of altering the means by which human needs are fulfilled, will have to commence now if the sustainable technologies are to be available when they are needed in 20 – 40 years time. As the concept matures, individual unit processes of the type that have been reported in this study, and elsewhere, may face a high rate of attrition. Nevertheless, success must ultimately depend on market forces as sustainability shifts inevitably from a regulatory and coercive to a market driven process.

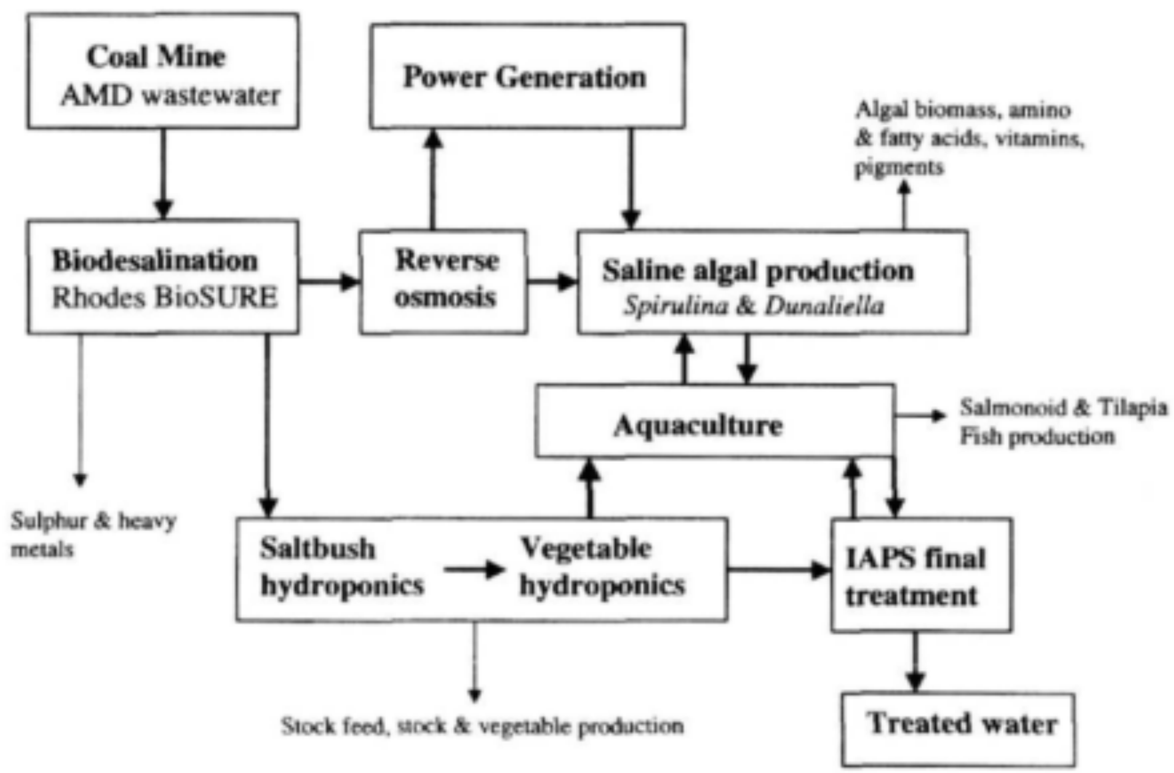

Figure 10. The Eskom Sustainable Development Project in 'integrated wastewater resource management' based on the biodesalination and treatment of coal mine wastewaters using the Rhodes BioSURE Process® as the initial process step. Following biodesalination the partly demineralised stream containing residual chloride salinity passes to reverse osmosis and back to power generation. The chloride saline reject stream passes to meso- and hyper-saline algal production systems. Residual partly treated water may be used in aquaculture, salt bush, stock rearing and intensive horticulture production operations. Treated water may pass via an IAPS polishing step to discharge in the public water system.

11 RESEARCH PRODUCTS

The completion of the WRC studies summarised here has resulted in the publication of 12 separate project reports. The details of these reports are listed in Appendix 1.

Student training has included 2 Post-Doctoral Fellows, 11 PhD and 14 MSc theses. Publication of the results of these studies is ongoing but currently includes 19 patents, 24 journal papers, and 8 articles of general scientific interest. Publication in conference proceedings includes 5 plenary and keynote papers, 24 international and 73 local conference presentations. The student training and publication outputs are reported in Appendix 2.

A number of industrial technology transfer exercises have been undertaken, involving the products of these studies, and are noted in Appendix 3. In addition, research spin-off developments which have resulted in associated follow-up research projects have been noted in Appendix 4 of this report.

ACKNOWLEDGMENTS

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. Given the number of different project involved these will be noted in each of the separate reports. Nevertheless, specific inputs affecting the overall study need acknowledgement here:

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- Chris Walwyn, of Grahamstown, who designed the cover.

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LIST OF ABBREVIATIONS

ABR	Anaerobic baffle reactor
ADB	Algal denitrifying bioreactor
AIWPS	Advanced integrated wastewater ponding systems
ALBAZOD	Algal bacterial zoogloeal detritus
AMD	Acid mine drainage
ANTRIC	Anaerobic trickle filter
ASPAM	Algal sulphate reducing ponding process for acid and metal wastewater treatment
BR	Baffle reactor
CCAP	Culture Collection for Algae and Protozoa
COD	Chemical oxygen demand
DACST	Department of Arts Culture Science and Technology
DEAT	Department of Environment Affairs and Tourism
D-HRAP	*Dunaliella* HRAP
DO	Dissolved oxygen
DPBR	Degrading packed bed reactor
DSP	Dual stage process
DWA	Department of Water Affairs (up to 1989)
DWAF	Department of Water affairs and Forestry (after 1989)
EBG	Environmental Biotechnology Group
EPA	Environmental Protection Agency
EPS	Extracellular polymeric substances
ERWAT	East Rand Water Care Company
ESKOM	Electricity Supply Commission
GM	Genetically modified
GMO	Genetically modified organism
HDS	High density sludge
ha	Hectare
HRAP	High rate algal ponds
HROP	High rate oxidation pond
HRT	Hydraulic retention time
IAPS	Integrated algal ponding systems
I-HRAP	Independent High Rate Algal Pond
IPWM	Integrated Pollution and Waste Management (White Paper)
LIRI	Leather Industries Research Institute
NEMA	National Environmental Management Act
NMR	Nuclear magnetic resonance
NSP	National Sanitation Policy
OECD	Organisation for Economic Cooperation and Development
PFP	Primary facultative pond
PSS	Primary sewage sludge
PWV	Pretoria Witwatersrand Vereeniging complex
R&D	Research and Development
RO	Reverse osmosis
PRG	Pollution Research Group
RSBR	Recycling Sludge Bed Reactor
SADC	Southern African Development Community

SCOWSAS	Standing Committee on Water Supply and Sanitation
SCP	Single cell protein
S-HRAP	*Spirulina* High Rate Algal Pond
SMME	Small micro and medium enterprise
SOBR	Sulphide oxidising bioreactor
SRB	Sulphate reducing bacteria
SRR	Single stage reactor
TDS	Total dissolved solids
TDIS	Total dissolved inorganic solids
TKN	Total Kjeldal nitrogen
UCT	University of Cape Town
UN	United Nations
UNDP	United Nations Development Programme
VFA	Volatile fatty acid
VIP	Ventilation improved privy
WCED	World Conference on Environment and Development
WISA	Water Institute of South Africa
WRC	Water Research Commission
WSP	Waste stabilisation pond

NOTATION

A wide range of terms has been used over the years by different authors to describe various configurations of ponding systems used in wastewater treatment and in algal biotechnology applications. This has created a certain confusion in the literature, and to avoid possible further confusion the following usage has been followed in this study:

- The term Advanced Integrated Wastewater Ponding System (AIWPS) refers to a specific trade-marked process application design. This ownership of name has been respected and care has been taken throughout not to use the term in a generic sense to cover the many forms of integrated ponding systems involving the use of algal photosynthesis. The terms Algal Integrated Ponding Systems (AIPS), and Integrated Algal High Rate Oxidation Ponding Process (IAHROP) which were used in this sense in the earlier part of this study to describe the hybrid algal ponding systems, the development of which was under consideration in this programme, has been changed to Integrated Algal Ponding Systems (IAPS) to avoid confusion;
- The IAPS is used here to refer generically to combinations of ponding system unit operations involving an algal component in their operation;
- The term High Rate Algal Pond (HRAP) has been used here and replaces High Rate Oxidation Pond (HROP) used in some literature references, as it is not necessarily inclusive of the algal component;
- The terms algae or micro-algae are used for convenience in the more traditional sense broadly covering both the eucaryotic algae as well as the cyanobacteria.

1 SALINITY, SANITATION AND WATER RESOURCE SUSTAINABILITY IN SOUTH AFRICA

1.1 SALINITY AND SANITATION

From its emergence in the early 1980s as a powerful source of social and political as well as environmental innovation, the sustainability idea has not only provided a sharpened focus on the interrelationships between economic and industrial growth and the bio-physical environment (so-called green issues), but has also included establishment of the now substantial connection between environment and human development (WCED, 1987, UN, 1992). This importantly includes the issue of poverty which is seen as both consequence and agent of environmental degradation. "Poverty reduces people's capacity to use resources in a sustainable manner; it intensifies pressure on the environment..." (WCED, 1987). The particular impact of pervasive poverty on environmentally sound land and water management in the developing world was noted in the Southern African Development Community (SADC) statement to the 1992 Rio Earth Summit: "If the poor sometimes behave in a manner that degrades the environment, it is not because they choose to do so. They only do so when they have no other choice" (Shela, 1996). Of the many factors impacting land and water use, salinity and sanitation have been increasingly identified as central issues in the implementation of the sustainability project in Southern Africa (DEAT, 1999).

The close connection between salinisation and desertification, while directly affecting rural poverty and hunger, is not only a problem of the developed world. It has been estimated that one quarter of the total land area of the world is now affected, or about 70% of all drylands. Desertification threatens the livelihoods of over 1 billion people in more than 100 countries (UN, 2001b), and the Africa Ministerial Statement to the Johannesburg World Summit on Sustainable Development (UN, 2001a), identified the Convention to Combat Desertification as a prime tool in the eradication of poverty on the continent. Undernourishment now affects over 200 million people in Africa, and food insecurity is directly related to the 500 million ha of land affected by soil degradation, including as much as 60% of agricultural land. "It is imperative, therefore, to reverse the current trend of land degradation and dwindling water resources for irrigation" as a prerequisite to implementing sustainable development in Africa.

However, irrigation production is particularly vulnerable and most irrigation systems worldwide are now salinised at some leve', with 80-110 million ha affected, and the area estimated to be increasing at a rate of 1 million ha.year^{-1} (Ramsar, 1996). In South Africa a creeping salinisation of the public water system, due to both natural and anthropogenic impacts, had been identified by the mid-1960s as the single most serious pollution threat facing the country (Commission of Enquiry into Water Matters, 1970). Together with other water related issues, this provided one of the principal motivating reasons for the establishment of the Water Research Commission (WRC) in 1971 (Water Research Act No. 34 of 1971). The recent State of the Environment Report (DEAT, 1999), indicates that over the intervening period the situation has continued to deteriorate in both South Africa and the SADC region.

Sanitation, including broadly the provision of drinking-water supply and waste disposal services, and associated impacts on health, has also been identified as a critical issue in breaking the cycle of poverty in the developing world. In Africa a majority of people still lack access to safe water and sanitation services, and consequently morbidity and mortality due to waterborne and water-related diseases are still very high. The African Ministerial statement has thus further noted that implementation of sustainable development depends on addressing the causes of ill-health including "endemic, parasitic and infectious diseases which have retarded the quality and productivity of Africa's human resources. Many have roots in environmental conditions under which people live, in poor environmental hygiene, inadequate access to resources, such as water and sanitation, and inadequate nutrition" (UN, 2001a).

The UN Secretary General's report on progress in implementing sustainable development over the 10 years since the Rio Earth Summit (UN, 2001b) does, however, note particular advances in provision of water and sanitation services. Some 438 million people in developing countries gained access to improved drinking water supplies in the 1990s. Over the same period 542 million people gained access to urban sanitation facilities. Nevertheless, these gains may be largely negated, and sustainability remains threatened by urban population growth. By 2025 it is estimated that 54% of the population in developing countries will reside in urban areas. The enormous additional burden on wastewater treatment facilities and solid waste management capacity will provide major obstacles to achieving water resource sustainability (UN, 2001b).

1.2 SUSTAINABILITY AND AGENDA 21 IN SOUTH AFRICA

Environmental and water resources management in South Africa has been transformed, over a period of a few years in the 1990s, by a legislative programme which has brought into law aspects of policy which are at the forefront of sustainable resource thinking internationally. The National Water Act (Act 36 of 1998), the Water Services Act (Act 108 of 1997), the National Environmental Management Act – NEMA, (Act 107 of 1998), and the Integrated Pollution and Waste Management (IPWM) White Paper (DEAT, 2000), represent a quantum shift in the State's approach to the environment, and are the product of an extended process of policy change linking sustainability and national development. The commitment to sustainability in the new legislation is driven by adoption of the Agenda 21 protocol at the United Nations Conference on Environment and Development, Rio de Janeiro, June 1992, (UN, 1992). This is one of around 20 other international environmental conventions to which South Africa is now signatory. The process targets continuing improvement of the human condition, without undermining the natural resource base on which this development depends.

While the National Water Act and Water Services Act provide specific focus on the sustainability of the water resource, and protection of the associated bio-physical environment, these Acts also provide for equity in distribution and the provision of basic water related services. The fundamental principle established is that water is a national resource, owned by the people of South Africa, and held in custodianship by the State. It allows for mechanisms to be put in place to manage water resources using a more holistic, ecologically-based approach, taking into account the entire water cycle. Probably the most significant innovation of the Act (section 16) is the provision for a basic reserve – the basic human needs reserve and the ecological reserve. The human reserve provides for the basic right of access to a minimum amount and quality of water for living and daily tasks – drinking, food preparation and personal hygiene. This is commonly put at 25 litres. $person^{-1}.day^{-1}$, and accessible at a distance of no more than 200 metres. The ecological reserve refers to the minimum quantity and quality of water necessary for the health of the ecosystem.

It is a basic provision of NEMA that the state embark on a process of institutionalising the concepts of sustainable development, and that an Annual Performance Report on Sustainable Development should audit the Government's response in respect of Agenda 21 commitments. The first National State of the Environment Report was released on 26 October, 1999 (DEAT,1999). Although much of the data had been previously available, this report importantly assembled for the first time a comprehensive overview and statistical profile of the state of the terrestrial, climatic and aquatic resource environments in South Africa, in addition to social, economic and political assessments. The Report has provided important inputs to the shaping of policy, the State's response to its commitment to sustainable development, and in determining priorities with respect to technological, socio-political and institutional measures, including the prioritisation of state-funded Research and Development (R&D) activity.

1.3 INTEGRATING MANAGEMENT OF SALINITY AND SANITATION: A WRC STUDY

At the heart of the environmental legislative programme is the principle of integration. It has been recognised that all elements of the environment are linked, and its management must therefore take account of the connection between them. The integration of environmental concerns into every area of human activity is central to the achievement of sustainable development objectives, and includes social, economic and institutional factors, in addition to the role of ecosystems within the bio-physical environment. This includes a more direct management of human influences on the integrity of complex natural ecosystems. It is argued that an ecosystems approach to the integrated management of land, water and living systems promotes the conservation and sustainable use of resources (UN, 2001b). In this regard the integration of pollution and waste management has been identified as a particular focus area in managing the environment, and the 2000 IPWM White Paper has identified these principles in pending legislation aimed at eliminating administrative fragmentation, and establishing direct linkage between the pollution and waste management functions (DEAT, 2000). It is now increasingly recognised that the boundaries between pollution and waste, and indeed that between wastes and resources, is an arbitrary one, and is dependent rather on their marginal utility, and the availability of technologies to address their beneficiation.

Chapter 18 of the Agenda 21 protocol on Sustainable Development relates to "Application of Integrated Approaches to the Development, Management and Use of Water Resources". It calls for the development of clean technologies which would control wastes in an integrated manner, including recycle and reuse, and based on a broad life-cycle analysis approach. These principles have also been incorporated in the IPWM White Paper (DEAT, 2000). Dependence on the technological capacity to deliver sustainability objectives has been frequently recognised, and the importance of investment in indigenous technology development, and the associated science and technology human resource capacity, has been widely promoted (UN, 1992, 2001a&b). In this regard the priority development of biotechnology as a science-based approach in dealing with waste treatment and water pollution control problems was identified in the Chapter 18 protocol (UN, 1992). Although since then environmental biotechnology has developed rapidly, together with agricultural and biomedical applications, this has, however, tended not to include priority focus on technologies for advancing sustainability goals in the developing world.

This report describes a WRC study which undertook the investigation of a biotechnology-based approach to the problems of salinity and sanitation, where potential technological linkages between these systems could lead to opportunities for an 'integrated wastewater resource management'. Beneficiation, as operations that add value by transforming materials from a raw-material status into finished products, had been identified as an important incentive in shifting the implementation of sustainablity and 'closed system' production goals, from regulatory to a market-driven implementation.

This study developed from work on the biotechnology of saline wastewater beneficiation undertaken in the Environmental Biotechnology Group (EBG) at Rhodes University during the late 1980s (Rose, 1991). Integrated Algal Ponding Systems (IAPS) formed the 'core technology' basis of these studies, providing a vehicle for the management of saline concentrates outside the fresh water system, and the linked beneficiation of organic wastes as carbon source reagents for useful environmental remediation work. The study included investigating the recovery of nutrients and the simultaneous beneficiation of saline and organic wastes in the form of algal bio-products, such as fine chemicals and high-value biomass.

These studies took shape in the climate around the 1987 World Commission on Environment and Development (WCED, 1987), and including the period leading up to the United Nations Conference on Environment and Development in Rio de Janiero (UN, 1992). These meetings initiated a particular focus on the problems of operationalising sustainability, and among its objectives included a search for technological models which could provide for, and facilitate, the integrated management of environmental resources, including wastes.

Around this time the WRC had established a specific portfolio on water supply and sanitation, and was a founder member of the Standing Committee on Water Supply and Sanitation (SCOWSAS). Referring to past deficits in service provision and policy thinking on sanitation in South Africa, the Draft White Paper on a National Sanitation Policy (DWAF, 1995), noted "farsighted action by, among others, the WRC which had stepped up its funding of research on sanitation for developing communities since about 1990". Also at around this time a number of other WRC activities made important inputs to the prioritisation and direction of future water-related research. The final NATSURV reports identified major trends in industrial effluent generation and related water pollution problems (WRC, 1989). A WRC salinity workshop (du Plessis, 1990), brought together two decades of work on salinity in South Africa, and identified critical issues to be addressed in dealing with this problem. The key issues of salinity and sanitation raised at that time provide an earlier echo of the priority water pollution problems identified in the IPWM White Paper (DEAT, 2000).

It was against this background that the WRC study on biotechnological approaches to the treatment and management of saline wastewaters commenced in 1990, with the appointment of the Rhodes EBG to undertake a one-year feasibility evaluation on research opportunities involved in the biotechnological linkage of the saline and sewage wastewater systems. This initial project (K5/410 – 'A biotechnological approach to the removal of organics from saline effluents'), undertook assessment of the wider technological implications of the approach, and was to make recommendations on the merits of a longer-term R&D investment in this area. The initiative led to a series of project studies over the following twelve-year period, undertaken by the EBG with WRC, and joint WRC/Industry support. This report summarises the R&D output associated with this undertaking.

2 ENVIRONMENTAL BIOTECHNOLOGY AND SUSTAINABILITY

The UN Secretary General's report on Implementing Agenda 21 (UN, 2001b) noted that, 10 years after the United Nations Conference on Environment and Development, biotechnology had developed into an economically important industry where, in some industrialised countries, it had emerged as a profitable field playing a strategic role in enhancing national competitiveness in the global economy. However, its potential contribution to sustainable development had not been fully realised.

Notwithstanding the rather low-profile focus on development issues, both technology and biotechnology have been the subject of an intense scrutiny which has examined their role as components of the overall environmental problem. The concept of technology as a powerful but neutral agent, entirely at the service of its user, has been questioned, and its role as a culturally potent force has been noted (Sachs, 1999). In terms of this controversy it is important to establish the wider role of both technology and biotechnology within the context of the WRC study to be reported here.

2.1 THE SUSTAINABILITY DISCOURSE

It is evident that the discourse surrounding sustainable development is complex, controversial and, indeed, highly politicised. While sustainability has emerged as a principal feature of social and political life in the 21st Century, it is driven, quite simply, by two apparently conflicting goals, now nearly universally pursued around the globe – the improvement of environmental quality on the one hand, while simultaneously achieving large and sustained increases in economic activity and human development on the other. Although some have seen the evolution of sustainable development as a "flag of convenience under which many ships sail" (Adams, 1993), the term 'sustainability', relating specifically to the resilience of bio-physical ecosystems, may nevertheless be studied and clearly distinguished from the different, but ultimately interdependent, political, economic and social contexts of 'sustainable development'.

Jansen (1997) has noted that the broad goal of achieving sustainability over the long-term requires the fundamental renewal of the whole means by which human needs are fulfilled. On this point the World Resources Institute study "Transforming Technology" (Heaton *et al*., 1991), provides one of the early landmark contributions to operationalising the sustainability concept. It was argued that reconciling the economic and environmental goals societies had set for themselves would be possible only through a revolutionary transformation in technology – "a shift, perhaps unprecedented in scope and pace, to new technologies that dramatically reduce environmental impact per unit of prosperity"(Speth, 1990). Given the revolutionary nature of the technological transformation that is required to achieve the fusion of economic and environmental objectives, it is necessary that technologies meet two principal criteria. First, they must transform human activities into resource-light consumption patterns, and second, in terms of non-renewable resource depletion, new technology is required to enable societies to live strictly off nature's income, rather than consuming its capital. Technological transformation for environmental sustainability is thus a process that reduces environmental damage, per unit of added value, fast enough to outpace production increases (Speth, 1990).

Some environmental economists have argued that depletions in 'natural capital' may be replaced by future developments in 'human capital' (Whelan, 1989), and specifically in the form of technological innovation. Since it is not possible to leave future generations with the same quantities of exhaustible resources that are available to current generations, sustainable development therefore requires technical progress in the use, extraction and development of renewable or reproducible resources which fulfill the same functions as exhaustible resources (Bowers, 1997). The pessimism of the Club of Rome's Meadows Report (Meadows *et al*., 1972), which predicted absolute resource scarcities by the end of the 20th Century, has largely been replaced by a view of the processes of economic growth as generating the innovation and technological improvements which tend to prevent the emergence of raw material shortages.

This has led to the development of a new environmental economics where growth is taken as part of the solution, and no longer part of the problem (Fritsch *et al*., 1993). Environmental concern emerges as a force propelling economic growth. Shifting consumer demand spurs innovation, trimming down resource usage lowers production costs, and environmental technology opens up new markets. The environmental predicament is redefined as a problem of efficient resource allocation. Here, natural resources are considered grossly undervalued, and therefore wastefully allocated, while human resources along with technology are under-utilised. Sachs (1999) has noted that the business objective for achieving "eco-efficiency" has emerged as a strategy of considerable innovative power.

The viewpoint is nevertheless still the subject of active debate and Sachs (1999) has also argued that particularly under competitive conditions, efficiency gains, no matter whether economic, ecological or in time, usually invite the conversion of capital, resources or time saved into a further expansion of output. Wackernagel and Rees (1997) have argued that it is often precisely the economic gains from improved technical efficiency that increase the rate of resource throughput. Thus rebound effects, arising directly or indirectly from technological efficiency gains, may result in new phases of expansion and, over the long-term, a net increase in the overall consumption of resources. This has led to a viewpoint that, far from being the solution it appears, technology is a major factor underlying many of the world's current problems (Drummond and Marsden, 1999).

Moore (1993) has argued that resources in the economic context are socially produced and culturally constituted entities, and can be "defined in relationship to the mode of production which seeks to make use of them through both the physical and mental activity of the user" (Harvey, 1977). Implicit in this view is the observation that the manner in which resources are used is, therefore, not cast in concrete, or the unresponsive victim of any economic system, but is amenable to change by purposeful human activity. The economic contexts in which this might take place is a closely related but separate issue.

Nevertheless, it needs to be noted that the matter is no foregone conclusion, and the apparent contradictions noted above clearly need to be taken into account in dealing with any progress which may be made towards the development of a sustainable future. It is in this regard that a 'closed system' approach has been proposed as a mechanism by which the goals of sustainability may be achieved. Here human activities and the associated technological environment needs to be detached as far as possible from the bio-physical environment related to natural systems. The 'closed system' calls for a technological thrust that will enable the transformation of industrial activity, and other anthropogenic impacts, from materials-intensive high-throughput processes to resource-light systems that use fuel and raw materials efficiently, rely on inputs with low environmental costs, generate little or no waste, recycle residuals, and release only benign effluents (Heaton *et al.*, 1991). Above all, the condition of sustainability can only be met where renewable resources ultimately replace the use of finite exhaustible reserves.

While fully functional and appropriately engineered 'closed systems' may still lie in the future, the development of 'integrated resource management' strategies has presented a route whereby a myriad of small incremental steps may lead, in time, to the implementation of grand plan 'closed systems' which do successfully effect a change in the means by which human needs are fulfilled.

Suzuki (2000) has examined factors constraining the development of 'closed systems' and notes that, in existing industries, achieving 'zero emissions' seems more difficult since eco-restructuring needs to start from the currently operating system, and this has already been fully optimised within the open market economy. The development of key technologies for the establishment of completely closed material cycles will depend, to some extent, on the development of new industry clusters established specifically around this concept. These developments are largely dependent on pro-active approaches and are among the prime long-term opportunities of environmental biotechnology.

Jansen (1997) has examined the requirements for operationalising sustainable development in Europe and notes that short term instruments, such as policy and system management approaches, including demand management strategies, are to be found typically in 5 year planning programmes. The development of integrated technologies, and environment-directed products, are located rather in 20 year environmental policy plans, and these longer-term approaches require that exploratory innovation in sustainable technology development becomes embedded into the overall R&D process. In identifying the critical role of the 'technology push' approach Jansen further notes that to meet the timetables set by the sustainability agenda, the breakthroughs in technology required will have to be initiated now to guarantee their availability in the next 2 to 4 decades.

2.2 BIOTECHNOLOGY

It is largely within the context of the dilemmas outlined above, and a search for a resolution of the contradictions apparent within the sustainablity discourse, that focus has fallen in particular on the potential of what became known in the 1980s as the new 'high technology' (Buttel, 1995), a clustering of innovation around information technology, new advanced materials and biotechnology. Roobeek (1995) has noted the revolutionary impact of this tripod of factors in triggering pervasive changes in the overall economic system, resulting in the emergence of a new techno-economic paradigm, and replacing declining 'Fordist' industrial production systems.

Freeman (1995) has identified biotechnology as a locomotive technology, and as a component of the new techno-economic paradigm. He sees it as still some way from entering a secondary swarming phase of innovation and imitation (Schumpeter, 1939), which he thinks may only occur as late as the second to fourth decades of the 21st Century.

He notes, however, that one reason for the intense research interest is that the unexpected can always happen in such a fast moving field.

Biotechnology is not one single technology, but a group of techniques culled from various disciplines around biology and chemical technology. It has been defined, by the European Federation of Biotechnology, as the integrated use of biochemistry, molecular genetics, microbiology and process technology in the application of microorganisms, cell cultures, or parts thereof for practical purposes (Roobeek, 1995). Its development may be traced in three broad phases including, firstly, the time-honoured traditional applications such as cheese, wine, beer, bread and yoghurt manufacture; then, secondly, developments in the bioprocess industry, largely after the 1940s, enabling full-scale production of antibiotics and enzymes, and large-scale wastewater treatment plants. Finally, since the 1970s, the 'new biotechnology' developments in genetic engineering, immunology and cell fusion techniques have emerged.

The means to effectively combine the genetic material of different organisms has provided an unprecedented degree of control over the evolutionary process – the selection of mutants from the wide variety of forms generated by natural genetic mutations – and therefore also their targeted application in bioprocess development. Theoretical understanding has advanced to the point where it has become possible to manage biological processes predictably, and as a result of increasing confidence, the subject has changed from an empirically-based technology into a science-based discipline.

After a decade of research moving from laboratory to market, primarily in genetically modified (GM) products in the agricultural and biomedical fields, some see a fourth wave of biotechnology now emerging. This involves a shift from a focus on discipline bound product markets to a more eclectic problem-centred utilisation of available bio-techniques from a wide range of disciplines. The focus here would be on problem-solving and creating products in a broad range of applications, including environmental biotechnology. Modern biotechnology thus increasingly combines both old and new technologies, and most people now see no sharp dividing line between the two, especially where the socio-economic impacts of the so-called techno-economic revolution affects the world economy. There is, however, generally less controversy with respect to environmental applications of biotechnology where the use of genetically modified organisms (GMO) is likely to be restricted for a long time due to widely acknowledged containment requirements. Here studies in the microbial ecology base, and applications of biogeochemistry in environmental bio-process development, has tended to provide the dominant paradigm.

2.3 ENVIRONMENTAL BIOTECHNOLOGY AND BENEFICIATION

The development of environmental applications of biotechnology has been driven in part by wider changes taking place in the world economy. Investigation into the modernisation of industrial economies by the Organisation for Economic Co-operation and Development (OECD) in the early 1980s (Hajer, 1995), and the broad consensus achieved between sustainability and development objectives through the Brundtlandt Report (WCED, 1987), and the Rio Convention (UN, 1992), are milestones associated with the emergence of a global market for environmental technology. Some estimate its value as approaching \$500-750 billion annually early this century (Sayler, 1997). The proportionate market share for environmental biotechnology is unclear, but Sayler (1997) estimates that if its scope is fully exploited, a very significant fraction of the environmental technology market would become available.

Environmental biotechnology, in its intersection between enquiries into the basic mechanisms of biology and the engineering of practical bio-process applications, has emerged as a productive source of innovation in addressing the many problems relating to sustainability. The foremost of these is the development and implementation of 'integrated resource management' strategies, and providing the means by which the demands of human activities on natural resources may be reduced. The recovery of value, in the integrated management of waste treatment operations, where the boundary between wastes and resources is challenged, acquires an additional significance in the developing world context, where economic activity and opportunities for employment are prime components of the overall sustainability equation.

As in other areas of biotechnology, environmental applications of biology have a long and well developed history. The 'old' environmental biotechnologies include traditional forms of waste disposal practised over millennia, but culminating in the early engineering of large-scale urban projects for water-borne sewage and its treatment, developed in the late 19th Century. A growing understanding of the biological processes involved in waste treatment led, in the post WW II period, to the increasing interaction between microbiology and engineering, resulting in the development of anaerobic digestion processes, and the design of high throughput wastewater treatment plants. Increasing awareness of pollution loads on the environment has seen the extension of these developments to other bioremediation applications, including dedicated industrial effluent treatment systems, reclamation and purification of drinking water, the biofiltration of air and waste gasses, the bioremediation of soil and land, and solid waste treatment.

Sayler (1997) has noted that where research and application in bioremediation and waste treatment had been largely driven by environmental policy and government regulation, and to a lesser extent by economics, a major shift had developed in these driving forces commencing in the mid-1990s. Economics and cost benefit issues are replacing regulatory drivers as primary considerations in environmental waste management and restoration. This trend is accompanied by a transition from a primary focus on bioremediation to a greater emphasis on pollution abatement, pollution prevention and environmental sustainability issues.

The shift from end-of-pipe treatment processes, to up-stream prevention and sustainable production practice, has resulted in a new wave of developments and process innovations, ranging from improved housekeeping practice to completely new manufacturing methods. Also involved is the development of the use of organisms in chemical processes and bioconversions of feedstock chemicals, environmentally stable enzymatic catalysis, biotransformations, biosensors, immuno-assays, and application of GMOs.

Beneficiation, referring to operations that add value by transforming materials from a raw-material status into finished products, has been a term more commonly associated with the mining and metals industry. However, product recovery from waste streams, and the recycling and reuse of wastes as input resources to the production process, has not only identified 'closed system' sustainability as an important potential long-term value-adding opportunity, but also an immediate source of profitability. The development of the beneficiation approach is seen as an important component in achieving sustainability and sustainable development objectives, by driving the shift from regulation and coercion to market-driven forces.

2.4 PRIORITISATION IN THE R&D PROCESS

More recently the identification of environmental technology R&D needs, particularly in the developing world, has been subjected to increasing focus. Studies by the World Bank (1996), and the OECD (1998), have emphasised the importance of policy formulation in the management of demands on natural resources such as water. Despite the investment of over $100 billion during the 1980s in the International Drinking Water and Sanitation Decade, the target of full access to water supply and sanitation for all was not reached. Nevertheless, impressive gains were made in which 1.3 billion people gained access to clean water, and 748 million to sanitation facilities. Drawing on lessons learned, the OECD urged countries to review their institutional framework, and to improve policies for 'integrated resource management' (Lake and Souare, 1997). Increasing emphasis has been placed on the role of government in setting policy, and of a demand-responsive management approach in effecting sustainable practice. The policy approach has focussed on the elasticity of water demand, and the implementation of demand management or suppression strategies, as an alternative to further supply-side projects, such as dam building programmes, aimed at augmentation of the dwindling water resource (Garn, 1998; Katz, 1998,Wolfensohn, 1998).

The severe mismatch in Africa between population size and technological development has been noted by Mutembwa (2000). Some international aid donor agencies have drawn attention to the problem of a perceived slow uptake of water technologies and practices as being responsible for water mismanagement in the developing world (OECD, 1998). A technology diffusion barrier has been identified as one of the major problems to be resolved, and implicit in this, is the view that all the technology needed has already been developed, and is available and waiting in the developed world. This has led to a move in some quarters to drop or reduce R&D investment in the developing world, and to shift emphasis to purely demand-response management strategies.

The UN Secretary General's report on 'Implementing Agenda 21' has noted the need for favourable access to, and transfer of, environmentally sound technologies, in particular to developing countries. It noted that progress in addressing the constraints on this technology transfer process had not been encouraging.

Clearly, policy formulation has a crucial role to play in the prioritisation of the R&D process. Nevertheless Abrams (1998) has warned against a simplistic 'silver bullet' approach, in dealing with the enthusiasm for demand management strategies. Comprehensive programmes in developing water sustainability should certainly involve more than just pricing mechanisms, but should also include a range of other issues such as education, public awareness, institutional efficiency and societal commitment, in addition to an ongoing process of technological innovation (OECD, 1998; Turton and Ohlsson, 1999: DEAT, 2000; Mutembwa, 2000).

Noorgaard (1994) has noted that diversity and innovation provide the most appropriate defence against an unpredictable future, and that innovation is an essential component of a co-evolving human development process. Clearly R&D and human resource capacity development are two sides of the same coin. The view taken here is that, notwithstanding the need for technology transfer, the indigenous R&D process not only deals with site-related issues of appropriateness and provides a fertile source for a process of locally-driven innovation, but the training of the human resource infrastructure provides a crucial contribution to empowering a nation to mount its own effective response in sustainable development.

In contrast to a simple emphasis on technology transfer as a 'silver bullet' for the developing world, the African Minister's statement (UN, 2001a) has importantly focussed on the potential of human resource development and the endogenous technology industry to make a notable contribution to sustainable development in the continent. "We recognise that harnessing science and technology requires action in several areas, including adequate financing, promoting the culture of innovation and science in our societies, appropriately managing intellectual property rights to promote increased science and technology activities within African countries, whilst minimising barriers of access to knowledge worldwide."

In this context the IPWM White Paper has noted the lack of variety in the availability of appropriate technologies for pollution control and waste management in the South African context (DEAT 2000). It also notes the close relationship between capacity, as promoted by sound scientific research and monitoring, the recognition of local knowledge and information, and the human resource development need associated with the education and training of pollution and waste management personnel.

2.5 CONCLUSIONS

The complexity and the controversial nature of the discourse in sustainability, development and biotechnology has required an attempt to clearly establish the overall context in which the WRC study, which has been reported here, has been pursued.

Technology is seen as an enabling prerequisite in operationalising sustainability in a dynamic and rapidly changing world. The study has been driven, to a certain extent, by a 'technology-push' approach, in common with trends in sustainable technology research management practice followed elsewhere. Here a back-casting approach sets an agenda for technological developments which will have to be initiated now if they are to be available when required sometime in the future. Environmental biotechnology as part of a fourth wave of biotechnology development, is an eclectic and pragmatic process, and its problem orientated approach, involving initially little GM application, will tend to redress anxieties about ethical and safety issues in biotechnology associated with GM systems.

Sustainable development implies sustainability in a dynamic process of local innovation focussed on local problem solving capacity. While technology transfer will be important in kick-starting the process, application as a basis of subsequent innovation must be locally driven. The human capacity to deliver on sustainable development objectives requires active investment in a training process in which both research and human resource development are inseparable components. Most of the work reported here thus relates directly to individual postgraduate student research programmes.

This study has focussed on a number of issues in salinity and sanitation sustainability, as a model system in environmental biotechnology. This has been used to explore the potential of waste beneficiation in transforming wastewaters, as resources or raw materials, into final or finished products. While it has not attempted to develop a comprehensive methodology for dealing with the manifold problems of salinity and sanitation pollution and waste management, it has focussed on individual aspects of the problem and the development of individual unit processes which might contribute to human resource development and the broader goals of 'closed system' production.

3 SALINITY AND SANITATION

The principles underpinning an integrated management for pollution and waste in South Africa have been articulated in the IPWM White Paper published in 2000, and which has broadly followed international trends in this area (DEAT, 2000). Pollution and waste are seen as components of a common problem, and in adopting a holistic approach to their management one of the main administrative objectives, to be addressed in the new legislation, was the fragmented and uncoordinated manner in which pollution and waste had previously been dealt with. This, together with insufficient resources to implement existing legislation, was seen as contributing largely to the unacceptably high levels of pollution and waste in South Africa.

As in the water and environment legislation which preceded it, sustainability provided the guiding principle underlying much of the policy developed in the IPWM White Paper (DEAT, 2000). Integrated pollution and waste management is driven by a vision of environmentally sustainable economic development and contributes to meeting the state's obligations with respect to Agenda 21, and other international agreements.

Waste is identified as a major source of pollution and the White Paper notes that the IPWM policy represents a paradigm shift from dealing with waste only after it is generated, the 'end-of-pipe' approach, towards pollution prevention and waste minimisation strategies. Integration is seen as providing for this requirement in a hierarchic approach aiming firstly at source control and prevention (avoidance, reduction, minimisation), secondly at impact management (recovery, recycle, re-use), and lastly at remediation (treatment) and disposal.

3.1 KEY WATER POLLUTION ISSUES

One of the significant contributions of the participative process, arising from the development of the IPWM policy, has been the identification of the key pollution issues facing the country in the three receiving media – water, air and land. Given the similarity to the earlier NATSURV prioritisation exercise on which the objectives of this WRC study were initially defined (WRC, 1989), six of the seven key water pollution issues are quoted directly from the IPWM White Paper (DEAT, 2000).

1. Salinisation of fresh water

The many impacts of excess salinisation on water resources include reduced crop yields, increased formation of scale and added corrosion in domestic and industrial water conveyance systems, as well as increased requirements for pre-treatment of water for selected industrial uses (such as boiler feed water).

2. Enrichment of fresh water bodies by nutrients

The accumulation of excess nutrients (e.g. phosphates and nitrates) in water bodies changes the composition and functioning of the natural biota, makes the environment less attractive for recreation and sport, causes the presence of toxic metabolites and taste and odour-causing compounds, and complicates water treatment.

3. Microbiological quality of water

Human settlements are the major source of deteriorating microbiological water quality. Disease-causing micro-organisms and parasites enter the water environment through (for example) partially treated sewage effluents, seepage and wash-off from inadequate sanitation, and leachate from waste disposal systems.

4. Harmful organic and inorganic compounds

South Africa is highly industrialised and hence at times carries the burden of industrial pollution, including trace metals and synthetic organic pollutants. Concern is not only for the potable use of water (since these compounds are not easily removed by conventional water treatment technology), but also for the aquatic organisms indirectly dependent on aquatic life, such as waterfowl.

5. Diffuse water pollution

Sources of severe water pollution include pit latrines, industrial seepage, agrochemicals in soil, fertilisers and insecticides, run-off from farm lands, contamination from animal wastes, informal settlements, thermal pollution by power plants and leaking sewerage pipes.

6. Marine pollution

The marine environment is impacted by off-shore exploitation of marine resources, off-shore air-lifting operations, the extensive relocation of sand dunes in the near shore area, oil spills from passing vessels, the seepage of sewage into coastal waters and sewage and industrial effluent discharge pipelines off the coast.

With the exception of sediment and silt migration, all the priority pollution issues noted in the IPWM White Paper relate directly to either dissolved solids problems (salts, metals, organics) or to the effects of poor, or non-existent, sanitation.

3.2 SALINITY

3.2.1 Nature of the Problem

Salinisation, the accumulation of dissolved inorganic salts, has long been regarded as one of the single most serious threats of pollution facing the public water system in South Africa (Commission Report,1970; Best,1984; DWA,1986; Stander,1987; du Plessis, 1990; DEAT, 2000; Urban-Econ, 2000). Although a great deal of effort has been expended in dealing with this problem over the past 30 years, the current position remains one of continuously increasing salinities; and a Department of Water Affairs and Forestry (DWAF) official observed that water quality management strategies and pollution control measures put in place to deal with the problem, including dilution, tended to conceal this underlying trend (Foster,1990).

Salinity is one of the most insidious and difficult to treat of environmental problems, and it may have both natural and anthropogenic causes.

3.2.1.1 Geological Salinity

Geological formations in South Africa, such as the Karroo shales, are well impregnated with salts, and when periodically inundated with flood waters are leached and, with an elevated water table, may give rise to highly saline base flows (Schultz,1988). This is especially apparent in the arid western region (Walmsley *et al.*, 1999). Evaporative losses and flow reduction in rivers due to upstream diversion, or drought conditions, will likewise raise salt levels.

Salinity is also the result of human productive activity (agricultural, industrial and urban), and is the inevitable result of water usage, especially where recycle plays an important role in the overall water economy, as is the case in the Vaal River system. It is the inevitable consequence of increased abstractions, consumptive use and return flows (Foster,1990).

3.2.1.2 Agricultural Salinity

Mankind has a long history of manipulating water resources for his own needs. The first major economic revolution, brought about by the enhancement of agricultural productivity through water control, first in the Middle East, and soon after at Mohenjo-Daro and Harappa in the Indus valley and then elsewhere, dates to sometime before the close of the fourth millennium BC (Toynbee, 1972). Sumerian irrigation is estimated to have supported a population of some 17-25 million people at its peak around 2000 BC. Progressive salinisation of irrigation land is thought to have led to declining productivity, an undermined economy, and finally to the collapse of this civilization (Sinnigen and Robinson, 1981). Today the 10 million people who now live in this area are net importers of food. Similar problems now face most irrigation systems worldwide (de Villiers, 1999).

The salinisation process is closely linked to changes brought about in the hydrological cycle by modification to the way water is routed through the landscape. Two fundamentally different processes occur in irrigation and dryland salinisation. Both may be responsible for the remobilisation of salts into the zone of production from the underlying aquifer, or the unsaturated vadose zone.

Nearly all irrigation water contains some salt which percolates to the water table and makes it increasingly brackish. Continuous irrigation, with the concurrent evapo-transpiration of saline water, results in the accumulation of salts in the upper soil layers, and can seriously affect plant growth and crop yields. The efficiency of irrigation application is optimised by adding an amount of water sufficient to meet the plant's water demand, as well as flushing any accumulated salts from the root zone. This flushing fraction is vital to the long term maintenance of low salt levels in the root zone. The salinisation process is accelerated in poorly drained and waterlogged soils, and is highly likely where the watertable lies consistently within 1-2 metres of the surface. In its final stages salinisation results in irreversible damage to the soil structure, and ultimately crystallisation of salts on the surface (Johl,1980). Fertilizers and pesticides may also be contributory factors where runoff and seepage will result in elevated salinities for downstream users.

Following the explosive development of agriculture this century around 17% of the world's agricultural land is now irrigated, with some countries relying almost exclusively on irrigated agriculture – Egypt 100%, and Pakistan 70%. However, salinity now impacts most irrigation systems at some level, with waterlogging and salinisation affecting 80-110 million ha fertile soil worldwide, and is estimated to be spreading at rate of about 1 million $ha.year^{-1}$ (Ramsar, 1996). In Pakistan two million ha irrigation land has been decommissioned due to salinity, and overall farm yields are down 30%. In USA 30% of all irrigated land also have yield reductions due to salinity (de Villiers, 1999).

In South Africa irrigation, especially in the dry areas, is also beset with this problem. A number of schemes have failed completely, and others are seriously affected, such as the Fish and Sundays River schemes (v.d.Merwe,1962., DWA, 1986). Herold and Bailey (1996) have described the impact of salinity on South Africa's largest irrigation area, the Vaalhartz Scheme.

Salinisation may also affect dryland farming practices, especially where indigenous bush clearing and the bringing into production of marginal land takes place in areas underlaid by saliniferous deposits. Cropping on dryland affects soil structure and increases water penetration, and may also accelerate salts release and base flow leaching to the water system. The Murray-Darling River basin area in Australia provides an extreme case of dryland salinisation which has followed the clearing of indigenous bush. Reduced evapotranspiration, especially due to clearing of eucalypt species, has allowed the water table to rise to very close to the surface, and bringing high concentrations of salts into the root zone of annual crops. Evaporative water loss results in salt accumulation in surface layers. Groundwater levels are estimated to have risen by up to 30 metres in south Western Australia since the 1880s, and it is estimated 1 to 1.5 million ha will be affected by 2010 (Evans, 1995). The water table has also risen in urban areas in Australia affecting foundations of buildings and roads, bridges, underground pipelines and other components of the built environment.

3.2.1.3 Irrigation Drainage

Segregation of saline irrigation drainage has been widely practised in the western US to combat waterlogging and salinisation effects, and the resulting saline waste stream is either impounded in farm evaporation ponds, or disposed via central collection facilities to the sea. The value of these saline ponds was computed initially simply in terms of disposal and relief provided to productive land, and management focussed mainly on salts, nutrients and pesticides. Later, however, ecosystem values of saline water impoundments have become apparent as they have been used as wildlife refuges and wetlands, and of particular note, as habitats in the flypath of large numbers of migratory waterfowl.

It is in connection with their wildlife refuge status that two saline impoundments in California, Kesterson Reservoir and the Salton Sea, reached notoriety in terms of environmental impacts. In the sense that these are among the best studied and recorded cases, they are considered here in some detail.

Kesterson Reservoir

Kesterson Reservoir, a 1200 acre site collecting saline irrigation tile drainage wastewaters, was constructed by the US Bureau of Reclamation in the San Joaquin Valley, central California. It was initially conceived as a collection point for drainage, prior to passing via a canal, yet to be constructed, to discharge in the San Francisco Bay area. It was declared a Wildlife Refuge in 1978, and in 1981 irrigation drainage became the Reservoir's sole source of water. By 1982 evaporative concentration of salts, and in particular selenium, boron and other trace elements, was found to have accumulated to toxic levels in associated plant and animal communities. High selenium levels were found to be responsible for increasing numbers of bird deaths, egg fragility, and stillborn and deformed chicks, and the US was found to be in default of the International Bird Migration Treaty. Drainage flow to Kesterson was halted in 1986 and contaminated ponds cleaned and filled (Presser, 1994).

Selenium is an important anti-oxidant associated with vitamin E activity in free-radical scavenging. In deficiency states heart disease, bone problems and cancers may be prominent effects. However, in excess, symptoms in animals include blind staggers, liver and kidney failures and tremors, respiratory failure and death. The EPA toxicology standard sets a selenium limit of 50 ppb in water.

The unforseen result of using irrigation drainage water to sustain wetland ecosystems in terminal waterbodies prompted the US Department of the Interior to create the National Irrigation Water Quality Programme, and to develop satellite imaging techniques for determining where else the problem might occur in the 66 000 mile^2 irrigated land in the Western US (Seiler, 1995). Upper Cetaceous and Tertiary marine sedimentary deposits in nearby mountains are the principal sources of selenium for contaminated areas in the San Joaquin Valley, and since drain water is reused for irrigation downstream, it can be a source of selenium in other areas, such as the Imperial Valley, which has no high selenium source of its own. An evaporation index exceeding 2.5 (annual free water surface evaporation/precipitation) was shown to be an effective basis for the separation of contaminated and uncontaminated areas. An area was considered contaminated where selenium levels exceeded the US EPA chronic criterion for the protection of freshwater aquatic life of 5 $\mu g.L^{-1}$ (Seiler, 1995).

The conclusions to be drawn from the Kesterson Reservoir case are that while saline wastewater impoundment offers an elementary low-tech solution to a substantial problem, it is not without its drawbacks. However, in the developing world, segregation of saline wastewaters may provide the only means to protect the fresh water resource. It is now apparent that pretreatment of the drainage waters to remove contaminating organics, metals and problematic trace elements, must be an essential prerequisite to the successful impoundment of saline wastewaters.

The Salton Sea

The Salton Sea is a terminal water body (365 mile^2) located east of San Diego, in a closed desert basin some 278 ft below sea level. It was accidentally filled by flood waters from the Colorado River in 1905, and as the recipient of agricultural drainage waters from the Imperial, Coachella and Mexicali Valleys, has become a saline lake, with salinity levels (44 000 $mg.L^{-1}$) somewhat higher than sea water (USBR, 2000). The Salton Sea is a polluted water body with increasing levels of salinity, nutrient loading, oxygen depletion, selenium, DDE (a breakdown product of DDT), other pesticides, raw sewage and storm water runoff. The Sea is well-known for its periodic bird die-offs – up to 150 000 birds at one time. Environmental protection groups warn pregnant women and children not to eat fish caught in the sea, and adults not to consume more than 1 $kg.^{-1}$ month, because of elevated selenium levels. Yet the sea has a productive sport fishery and provides an important migratory and resident bird habitat in the Pacific Flyway. It is inhabited seasonally by millions of birds, with up to 400 species recorded. Because of the loss of about 90% of wetlands in California, the Salton Sea serves an important role in the international and local conservation of migratory birds. Some bird species are now entirely dependent on the Sea due to the bioenergetics associated with food availability, travel distances between migration stop-over points, and body condition relative to breeding success (USBR, 2000).

There are serious concerns about the health of this ecosystem, and the Salton Sea Reclamation Act of 1998 was passed by the US Government to undertake a restoration process to relieve the serious environmental stresses. The project is expected to have an economic payback in addition to ecological and recreational benefits. Its five principal goals are to maintain the Sea as a repository for agricultural drainage, provide a safe wildlife ecosystem, restore recreational uses, maintain a viable sport fishery, and enhance economic development opportunities.

Apart from presenting another case illustrating the potential problems associated with the impoundment of saline drainage wastewaters, the findings of the restoration project illustrate the driving force available to sustainability management, where value-adding beneficiation functions can be incorporated into the overall solution.

3.2.1.4 Industrial Salinity

Industrial and urban activity can result in the development of a pattern of salinisation from its wastes comparable in extent to that in agriculture, where rising salt levels are not only a threat to downstream land, but also add an unacceptable cost to domestic and industrial users (Heyneke,1981 & 1987; Heyneke & McCulloch,1982; Urban-Econ, 2000). This includes the direct discharge of point source industrial and sewage treatment effluents, saline underground water pumped by the mines, and runoff and seepage from industrial and urban areas including mine dumps and atmospheric deposition (Jones *et al.* 1989; Scott 1995).

The Gauteng conurbation complex in South Africa provides a case study in industrial salinisation, with a long history of problems plaguing the supply of fresh water (Laburn,1979, Herold & Triebel,1990). The upper Klip River Valley and Zuurbekom wells, which supplied the early development of gold mining on the Witwatersrand, were soon to prove inadequate and were eventually abandoned due to seepage contamination. The Vaal Barrage was constructed in 1922, and then the Vaal Dam in 1938, but these supplies have also proved inadequate, and are now augmented from inter-basin transfers from as far afield as the Tugela, Usutu and the Orange Rivers. One of the major problems is that the Vaal tributaries which drain the Witwatersrand, the Klip and Zuikerbosch Rivers, discharge their saline polluted waters above the Vaal Barrage. To overcome this problem the Zuikerbosch Water Purification Works intake was built upstream of these discharge points in 1949. Soon, however, saline water was being sucked upstream which led, in 1969, to the construction of a pipeline, and in 1983 of a canal, to feed fresh water directly to this intake from the Vaal Dam without entering the river's water course.

Given the situation of rising demand, a high priority is placed on water conservation and recycle in order to meet current and future estimated off-take requirements (DWAF, 1989a). Rand Water Board system operating rules have been aimed at minimising spillage of water from the Vaal Barrage. About one third of the effluent emanating from the Gauteng PWV complex drains back to the Vaal River, its primary water source. In the case of the Southern PWV 64% of water supplied is returned as effluent with nearly 300 $mg.L^{-1}$ total dissolved solids (TDS) added in each cycle of use (Herold and Triebel,1990). Reports by Heyneke (1981 & 1987), Steffen, Robertson & Kirsten (1989) and Urban-Econ (2000) have attempted to compute the cost to consumers of the Vaal River salinisation problem. Herold and Bailey (1996) have drawn attention to the consequences for downstream users, including particularly the Vaalhartz irrigation scheme.

Salinisation trends have presented increasing threats in the Berg and Buffalo Rivers, and in a number of rivers in Kwa Zulu-Natal (Hart, 1982; DWA,1986; Walmsley *et al.*, 1999).

3.2.1.5 Mine Drainage

Pollution of surface waters with acid mine drainage (AMD) follows geochemical trauma induced by mining operations, and the resulting impact on the environment of ferric oxide 'Yellow Boy' precipitates has been known at least since Roman times (Wildeman *et al.*,1991). The biological and physico-chemical processes giving rise to pyrite oxidation, acid formation and heavy metal solubilisation have been well described and are comprehensively reviewed by Kuenen and Robertsen (1992), Pronk and Johnson (1992), Robb (1994) and Johnson (1995).

The extent of AMD impact on the environment may vary from the restricted pollution of small streams to quite profound perturbations of geohydrological systems on a regional basis. The Witwatersrand gold fields, exploited along a strike of 480 km, and to depths of over 4 km, provides a case study of the latter, where pumping rates of up to 130 $ML.day^{-1}$ in some mines is required to prevent flooding (Funke 1990). This water is typically acidic with total dissolved inorganic solids (TDIS) around 3500 $mg.L^{-1}$, mainly as sulphate, chloride and iron salts (Pulles *et al.*, 1995), and it has been estimated that over 400 000 tons of salinity from this source reaches the Vaal River annually. Apart from adding substantial costs to water provision and consumers (Heyneke 1987), the salt load from mining activities has contributed significantly to the salinisation of downstream irrigation land (Herold and Bailey 1996).

It has been estimated that when mine pumping operations finally cease, filling of the voids would occur within a decade, and to be followed by long-term AMD flows (Scott 1995). In the case of 'vestigial acidity' the void flushing process may be completed in 40 – 50 years. However, where 'juvenile acidity' occurs, arising from on-going pyrite oxidation in the zone of water table fluctuation, AMD flows may be expected to continue for many hundreds of years, until the inventory of the pyrite deposit is finally exhausted (Younger *et al.*,1997). The long-term nature of the problem, potentially extending over generations, and the large volumes of AMD requiring pumping and treatment (possibly 500 $ML.day^{-1}$), present particular technological challenges for the design of appropriate and sustainable remedial interventions. This has focussed interest on the advantages of low-cost, quasi-passive systems associated with biological approaches to AMD treatment, among the many physico-chemical processes now available.

3.2.2 Remedial Interventions

Three basic strategies are available for dealing with the problem of salts accumulation in a water system – prevention, dilution and segregation – or more commonly, combinations of these general approaches.

3.2.2.1 Prevention

Current trends in the shift from 'end-of-pipe' treatment to 'integrated wastewater resource management' approaches require implementation of the ultimate solution – to ensure that salts do not enter the water system in the first place. Both policy and resource management strategies have been intensively explored, especially within the context of sustainable resource use. Successes achieved in developing countries in this area have been reported by the World Bank's Greening Industry Report (Wheeler, 1999). This report, nevertheless, also notes the many failed attempts to import regulatory models from industrial countries, and that conventional 'command-and-control' strategies have generally not worked well. Participatory regulation, direct pollution charges, and public disclosure operate through expected penalties, and place prevention strategies on a solid economic foundation. The report also notes the simultaneous need to promote emissions reduction by lowering the costs of abatement.

3.2.2.2 Dilution

Dilution requires that a part of the fresh water resource be employed to ensure that TDS levels do not rise above critical thresholds.

In 1975 a programme was undertaken to develop a hydro-salinity model to simulate the movement of water and salt through the Vaal River/PWV complex, and enable a treatment of the complicated interdependence of factors necessary to predict the outcome of any particular course of action in this system (Herold, 1980, Stewart, Sviridov & Oliver,1985). Subsequent application reports on the blending option have appeared (Stewart, Sviridov & Oliver,1988a and 1988b; DWAF,1990). On the basis of these findings a blending scheme was identified as being the most cost-effective and ameliorative measure (Herold & Triebel,1990). In the blending scheme fresh water is drawn from the Vaal Dam and blended with downstream water to even out salinity peaks, and maintain a target of 300 $mg.L^{-1}$ TDS. Release of water from the Vaal Barrage is caught in the Bloemhof Dam, which feeds irrigation users including the Vaal-Hartz Scheme.

Du Plessis (1984) has identified the unit cost associated with mineralization as being very much smaller for irrigation than for urban use. Nevertheless, the disbenefits of increasing soil salinity for downstream users will accumulate in subsequent years (Herold and Bailey 1996). The process is inherently wasteful of fresh water, and depends on adequate supplies which are not assured. Herold & Triebel (1990) warn that too ambitious a blending target cannot be maintained indefinitely without incurring a severe penalty in terms of system yield, given anticipated growth in water demand for the PWV area over the following decades. While DWAF viewed the dilution and blending option as a short term or temporary solution, and favours, rather, the application of control measures aimed in the long-term at the source of saline pollution (Stander, 1987), the blending option remains the major salinity strategy in place for the Vaal River system.

3.2.2.3 Segregation

Segregation of the total saline waste stream, or a concentrated component of it such as desalination brines, is an elementary option available in many situations, and may be required, especially in the developing world, to ensure the ultimate sustainability of the water resource.

Solar evaporation ponds have been widely used for the disposal of saline industrial effluents, and in irrigation areas where alternative routes are not available for disposal of tile drainage flows. As already noted, where these ponding systems have developed into important wetlands and wild life refuge sites, especially for water fowl, some form of pre-treatment is necessary to limit the concentration of potentially toxic components, and impacts on the wildlife populating them.

The 1970 Commission of Enquiry into Water Matters identified desalination as a research goal to be pursued for expansion of existing water supplies, for the prevention of point source pollution, and to increase the number of cycles of reuse of water in industry. The WRC has actively funded research in this area which has resulted in the local development of reverse osmosis (RO), and cross flow ultra-filtration membrane technology, at the Institute of Polymer Research, Stellenbosch University. This technology has been successfully commercialised and practical applications of the system have been demonstrated for power station boiler feed water demineralization, and the desalination of mine waters (Botha,1984; Stewart, Sviridov & Oliver,1986; Buckley *et al.*, 1987; Hart *et al.*, 1987). A preliminary costing of large-scale side stream RO desalination of Vaal River water has been undertaken (Stewart, Sviridov & Oliver,1988c). Removal of particulates and colloidal organics has been identified as a necessary prerequisite for cost effective desalination of organic effluents (Neytzell-de Wilde *et al.*, 1987). Here also appropriate cross flow microfiltration technology has been developed by the Pollution Research Group (PRG), Department of Chemical Engineering at Natal University, and likewise subsequently commercialised (Treffry-Goatly *et al.*, 1983., Groves *et al.*,1985; Neytzell-de Wilde,1987).

Large-scale side stream desalination has been considered in the United States, with the Yuma desalting plant in the lower Colorado Valley planned to provide the world's largest membrane desalination project. Provision was made for the desalination of 300 $ML.day^{-1}$ agricultural drainage water from the Wellton-Mohawk Irrigation District, and the use of the treated stream as blend water to maintain a prerequisite salinity for the Colorado River as it passes into Mexico. An 85 km by-pass canal will discharge the reject brine stream to the Santa Clara Slough in the Gulf of Mexico (USBR, 2000).

Desalination on a larger scale could be particularly appropriate in cases where high salt loads are contributed in relatively small volumes. Mine dewatering and mine-dump seepage produce 25% of the annual salt load reaching the Vaal Barrage. This is discharged in only 5% of effluent volume (Jones *et al.*,1989). In contrast, diffuse sources of salinity, which contribute 40% of salt tonnages, are contained in the total storm water runoff, making this a difficult source to treat. Industry and sewage contributes 35% of total salt load in 32% of total volume (DWA,1986). Industries identified, where desalination could play an important role, are power generation, chemical, iron and steel, pulp and paper, textile, mining, food manufacture and processing, and the tanning and hides and skins curing industries (Botha,1984; DWA,1986).

The Department of Water Affairs (DWA) "Salts" project (DWAF, 1989b) surveyed sources of saline effluent in a number of Witwatersrand towns and cities, conducted on an industry by industry, and a product by-product, basis. The objective was to identify, and quantify, industrial sources of inorganic salt loads, and enable assessment of the feasibility of segregating the saline portion of the total effluent for separate removal to treatment facilities. The results, while provisional and not comprehensive, did indicate that a significant portion of the increased total salt load leaving the municipalities in their effluents could be isolated in a very small fraction of the total volume. In one example, 60% of increased TDS caused by the industries surveyed could be practically segregated in only 8% of their total effluent volume. Expressed differently, for the whole town this amounted to 10% of the total TDS added to the municipal effluent, and was contained in only 0,45% of their total effluent volume. The potential for further improvement was noted in the report, especially where incentives could be provided for improved manufacturing-process housekeeping. The report noted that membrane desalination processes applied at point source could further reduce the volumes of saline effluent to be handled.

3.2.2.4 Brine Disposal: the Dilemma of Salinity Treatment

Any treatment approach which incorporates a component of the segregation strategy has ultimately to address the same critical question – what to do with the brine wastes?

Buckley *et al*. (1987) have commented that the lack of provision of adequate methods of brine disposal has rendered the authorities responsible for pollution control powerless to enforce the desalination of saline effluents, despite legislation available to do so. Whereas disposal sites for virtually all solid, toxic and other wastes can be found or engineered, sites for the effective disposal of brines have not been investigated sufficiently (DWA,1986).

Numerous methods for the handling of brine concentrates are described in the literature, and some of the following have been considered in South Africa:

- ❑ The creation of salt water sinks or lakes that can be used for recreational purposes;
- ❑ Solar evaporation ponding with the production of a solid salt product;
- ❑ Saline algal aquaculture for the production of high value chemicals, biomass or fish;
- ❑ Co-disposal on solid waste disposal sites, mine tailing dams and ash dams at power stations;
- ❑ Use in manufacturing processes such as ash quenching;
- ❑ Deep well injection and dumping in disused mines;
- ❑ Transport to the coast by pipeline and discharge to sea;
- ❑ The recovery of marketable products such as soda ash;
- ❑ Incorporation into products such as fluting and liner board made by the paper industry;
- ❑ Vapour compression evaporation and crystallisation;
- ❑ Irrigation directly onto land;
- ❑ Enhancement of wetlands and agro-forestry;
- ❑ Electricity production using solar brine ponds;

(DWA, 1986; Stander, 1987; Fijen, 1988; Moolman, 1990; Marquart, 1990;Rose, 1991; Rose and Cowan 1992 a,b,c; Rose *et al*., 1992,1996&1998).

Where a brine concentrate approach is to be adopted, it has been suggested that local authorities will have to provide, and operate, central facilities, such as evaporation ponds, of sufficient capacity to absorb locally produced brines from either direct desalination or the segregation of saline effluents (Stander, 1987). State involvement in the establishment and operation of regional facilities may be warranted. The full cost of these facilities should be recovered from the brine producers in keeping with the principle 'the polluter pays'. This price could prove to be substantial. The cost of providing salt sinks has been examined for the DWA by Stewart, Sviridov & Oliver(1985), and in a study on RO desalination of water supply for lower Vaal River users, the cost of brine disposal was estimated at 10% of the total cost of plant. This figure would escalate several fold if plastic pond lining was to be used, as it should, to prevent ground water contamination (Stewart, Sviridov & Oliver,1988c).

3.2.2.5 Brine Disposal – Problem or Resource?

The principle that must govern any solution to the salinity problem is that it must not create more environmental problems than it solves, and the cost effectiveness of a segregation strategy, and also socio-economic cost benefits, should be borne in mind. Vandevivere and Verstraete (2001), in identifying future research needs in environmental biotechnology, point out that many conventional treatment techniques in current use provide an often perfect illustration of Murphy's Law – they merely transform one problem into another. In other words, the solution to the problem must not cost more than the cost of the problem.

The gravity, central relevance and long-term implications of the decisions to dilute or segregate, have been noted by Stander (1987). In concluding a detailed assessment of the salinity issue, he warned that opting for easy solutions for present day problems could result in an enormous debt burden for future generations, for whom the cost of solutions would then be either exorbitant or prohibitive . "This would be an awesome burden of guilt for the administrator, the researcher and the industrialist" (Stander, 1987).

While 'clean technology' and prevention strategies offer the ideal goal, it is evident that numerous instances do occur where a segregation strategy may provide the only option to prevent serious, and possibly permanent, degradation of the national water resource and the environment. This is especially obvious in the developing world where technological options available to deal with the salinity problem may be quite limited.

The incentive to manage the saline waste is clearly an integral part of the salinity problem itself, and costs associated with its disposal are a major limitation in the development of long-term strategies to deal with the problem. Since the principle of cost, in its widest sense, will dictate the most appropriate solutions to the problem, those technological options which offer the potential of value recovery in some form or other, would warrant particular attention. Recovery of value could imply a wide range of options, as noted above, but where the direct recovery of a by-product is implied, the generation of credits of this type, against waste disposal, has been a well established concept in improving the cost effectiveness of industrial processes (Hacking,1986).

The principle of value recovery is not new to waste management, and while exercising caution with regard to oversimplification, wastes have, nevertheless, been regarded as something of a golden opportunity for biotechnology. The boundary between wastes and by-products is arbitrary – where utility increases, a waste becomes a by-product. The value of wastes is determined by their opportunity costs, and this increasingly acquires a higher negative value with rising disposal charges and penalties imposed by environmental legislation. As environmental awareness increases, rising waste treatment costs become more acceptable to society and industry. This eventually tips the balance in favour of integrating waste treatment and some form of production, especially of microbial products.

The beneficiation of wastes as by-products can have a decisive impact on the economic viability of industries producing them.

This was recognised at the WRC workshop where South Africa's future salinity research requirements were prioritised (du Plessis,1990). Alternative use for saline water and salinity control were identified as among those research needs with the highest priority, second only to the existing programmes set up to assess future salinisation trends. The final NATSURV report identified similar research priorities in this field (WRC,1989).

While no general rules apply, it seems that in particular cases of water pollution, the identification of opportunity value may be the only way to ensure long-term environmental sustainability. Investment in incentive-driven research, and investigation of value-adding opportunities to drive effectively managed segregation strategies, has been identified elsewhere. An important aspect of the Salton Sea Restoration Project has been to include the development of economic benefits and the enhancement of recreational uses as principal drivers in the reclamation of healthy fish and wildlife resources, and their habitats (USBR, 2000). The Australian National Dry Land Salinity Programme has set up a special study project on Options for Productive Use of Salinity – OPUS, which is tasked to investigate opportunities and incentives available in adding value to saline wastes (NDSP, 1999). Initial findings in this study have identified numerous opportunities in saline agronomy, forage halophytes, horticulture, innovative industries and aquaculture, including production of algal bioproducts.

Value recovery, then, plays a potentially pivotal role in driving 'integrated wastewater resource management' objectives, and it is in this sense that the concept of value recovery, as a principle for placing the sustainability of salinity remediation solutions on a solid economic foundation, has provided a basic objective of the WRC programme reported here. It has been argued that since amelioration of cost is at the root of the problem, what is required in defining the research direction is a change in mindset, and that potential of brine wastes be re-evaluated as a resource rather than a problem.

3.3 SANITATION

Sanitation refers to a broad range of issues including physical infrastructure, provision of water hygiene-related behaviour and disposal of wastewater, excreta and other solid wastes. At its core, sanitation is a problem of pollution which, like most other human activity, results in changes to the environment and especially to freshwater ecosystems. While the maintenance and protection of the natural resource base remains a prerequisite for durable services, Abrams (1998) has noted the problems of dereliction rate and failure of treatment installations, as important impacts on sustainability of services. At this level, he notes, sustainability is very simple. It is whether or not something continues to work over time. If the system works then all of the many elements required for sustainability must have been in place. "There must have been money for recurring expenses and for the occasional repair, there must have been acceptance by the consumers of the service, the source supplying the service must have been adequate, the design must have been properly done and there must have been sound construction" (Abrams, 1998). In this regard sustainability includes technical issues, social factors, financial elements, the natural environment, durable gender equity and empowerment, and institutional arrangements.

The World Bank has defined sustainable development as development that lasts (World Bank, 1992).

The full effects of poor sanitation in South Africa have been documented in the National Sanitation Policy (NSP, 1996). The impact of inadequate sanitation on the health of the poor is significant in terms of the quality of life, and the education and development potential of communities. In terms of economic impacts, poor health keeps families in a cycle of poverty and lost income. The national cost of lost productivity, reduced educational potential and curative health care is substantial. In its environmental effects, inadequate sanitation leads to dispersed pollution of water sources, and this in turn increases the cost of downstream water treatment, as well as the risk of disease for communities who use untreated water.

One gram of human faeces may contain around a million bacteria, 10 000 viruses, 1000 parasite cysts and 100 parasite eggs. In addition children in developing countries commonly carry up to 1000 hookworms, roundworms and whipworms causing anaemia and other debilitating conditions (WSSCC, 2000a). Spread of these infectious entities may be simply due to open-air defecation, as is accepted practice in many parts of the developing world – around 88% of the rural population in West Bengal (WSSCC 2000b). In China it is estimated 600 million rural residents do not have sanitary latrines, and it has been common practice to use excreta as fertilizer for field crops. As a result some 530 million people are infected with intestinal worms, including up to 90% of children in poorer areas. Worm infection and frequent diarrhoea, due to unsafe excreta disposal and poor hygiene, are the major factors contributing to stunted growth, which affects over 39% of rural Chinese children (WSSCC, 2000c).

It is estimated that in the developing world some 40% of the rural population still lack an adequate water supply, and 60% are without access to sanitation. Lake and Souare (1997) estimate 460 million Africans are without proper sanitation facilities and water-related diseases kill an estimated 3 million Africans annually, while also taking a hidden toll in lost productivity. Cholera, typhoid and dysentery are problems particularly in Mozambique, Malawi, Zambia and Tanzania. Other water related health hazards in Africa include malaria, bilharzia and river blindness (Shela, 1996).

It had been estimated in 1995 that around 21 million South Africans did not have access to adequate sanitation, which includes 31% of the urban population, and up to 85% of the rural population, and some 2 million people still relied on the bucket system (National Sanitation Task Team, 1995). Around 45% of the rural population were estimated to be without adequate water supply (Palmer, 1998). The health implications of this situation are severe, and diarrhoeal diseases are the primary cause of child deaths (27.4% in the 1-4 age group), and the second largest cause of infant deaths under 1 year, after perinatal causes (National Sanitation Task Team, 1995).

The National Sanitation Task Team, a collaborative effort of six government departments, was established to deal with the problems of water and sanitation in South Africa, and after a wide process of consultation the National Sanitation Policy was published in October 1996 (NSP, 1996). The broad stated objective was to achieve an improvement in the quality of life, and it was noted that nearly half of South Africa's population have not received delivery of the undertaking made in the Constitution that, "Every person shall have the right to an environment which is not detrimental to his or her health or well-being" (National Sanitation Task Team, 1995). The principal areas of focus of the initiative were the safe disposal of human wastes and domestic wastewater, in conjunction with appropriate health and hygiene practices.

More recently the South African Advertising Research Council has noted the effects of these initiatives (SAARC, 2002). Some 76% of urban households now have piped water, and water delivery had improved by 85% in rural communities. However, still only 42% of rural households had piped water.

The NSP notes that sanitation is more than toilets, it is a larger process aimed at the individual, the home and the community, which must include health and hygiene education as well as sustainably improved toilet facilities, water supply and methods of removal of dirty water and household refuse. The Policy recognises that while in the past community sanitation had been seen primarily as a technical issue, it is now recognised that other elements of sanitation, particularly social issues and health and hygiene education, are also of central importance. These insights have had a major impact in the definition of the principles on which the implementation of the policy is based.

The NSP states that sanitation development is first and foremost a household responsibility and should be demand-driven and community based. While it is recognised that basic services are a human right, the role of government is to create an enabling environment through which all South Africans can access support in obtaining services. But in the end it is the individuals and communities who are responsible. Water has an economic value, and the way in which sanitation services are provided must take into account the growing scarcity of good quality water in South Africa. The pollution of water resources also has an economic cost, and the true value of services must reflect this in such a way that long-term sustainability and economic growth are not undermined. In this regard the 'user pays' principle applies. Sanitation systems must be sustainable, which means they must be affordable to the service provider, and payment by the user is essential to ensure this (NSP, 1996).

The demand-driven approach of the NSP is in the forefront of international thinking on water supply and sanitation development. In opening a World Bank sponsored community water supply and sanitation conference, Wolfensohn (1998) noted the changes which have mandated a transition from top-down, supply-driven, approaches to a more demand-responsive approach in service delivery. The sustainability of the approach is driven by treating water as an economic good, as well as a social good. In a six-country study undertaken to clarify the impact of the demand-response approach, Katz (1998) found the likelihood of sustainability of rural water systems was significantly increased. The UNDP-World Bank Water and Sanitation Programme reports that the demand-driven approach tends to promote innovation and flexibility. In monitoring the transition from supply-oriented services it is noted that new ways of thinking about project design are required in order to develop incentives for the wide range of stakeholder groups concerned, and increased scope is provided for private sector and non-governmental organisations involved in the implementation of rural water and sanitation projects (Garn, 1998). Kasrils (2000) has, nevertheless, warned that in the case of the poorest of the poor in South African rural areas, even minimal costs may be more than can be sustained.

3.3.1 Sanitation: Problem or Resource?

The NSP (1996) has noted the particular role of the private sector in the provision of sanitation services, especially where this results in local business development, and provides employment. It notes that the training of small-scale builders will improve both the quality and sustainability of sanitation products. Local availability of skills and materials has an important bearing on the choice of technology, and design development should maximise the use of these resources, in order to stimulate local economic activity. The Mvula Trust has recorded a number of case studies where this principle has been successfully applied in rural Southern Africa (Palmer, 1998).

In this respect it is important to note that the NSP (1996) recognises that improvement of household sanitation is a process which keeps pace with a household's aspirations. An upgrading process, from the basic level of service such as ventilation improved privy (VIP) and septic tank systems, to low-flow and finally full water borne sewage, should be considered at the planning stage, and incorporated into designs at the outset. A hierarchy of adequate sanitation options is generally associated with higher costs, greater use of water and improved convenience and status. For the organisation responsible for managing the sanitation system, this means both higher costs to be recovered from users, and increasing operational and maintenance complexity (NSP, 1996).

The provision of technical support is regarded as a vital element of the NSP, and it calls for the development of guidelines for the design and construction of different sanitation technologies (NSP, 1996). In calling for linkages with other programmes, and in order to promote the sanitation provision initiative, the NSP notes that one of the specific objectives to be met is that process pilot activities be undertaken in support of the promotion of adequate sanitation systems (NSP, 1996). The WRC have taken a leading role in this respect with the development of preliminary guidelines for private sector participation in water supply and sanitation services; planning and implementation of water projects; guidelines for developers and local authorities and guidelines for the provision of low-flow on-site sanitation systems – LOFLOS.

Notwithstanding these developments, Mutembwa (2000) has noted a re-engineering of urban drainage system in Zimbabwe for resource recovery and protection of drinking water supplies. Human wastes provide around 90% of the annual fertilizer values required to grow the 250 kg cereals consumed over the same period of time. The recovery of these values has become an important objective in the development of integrated urban water management concepts, and provides critical inputs to sustainability objectives, particularly in the developing world. Technological options to effect this recovery of value are not trivial but, here again, private initiative will be a powerful incentive where recovery of value from the treatment process is available to offset the costs of the treatment operation.

3.4 CONCLUSIONS

The implementation of an integrated strategy for the management of pollution and wastes not only advances the overall objective of sustainability, but also provides a legislative mechanism in which market forces may move towards waste beneficiation and adding value in closed-loop systems. A shift from command-and-control mechanisms to demand responsiveness is an important prerequisite, and waste clubs are a significant step in this regard.

The investigation of potential in an integrated management of saline pollution and domestic and industrial wastewater treatment presents a useful model system for exploring the feasibility, and the development, of enabling technologies for advancing the 'closed system' objective. The role of beneficiation and value addition as a principal incentive in driving this process over the long-term has been widely noted. The WRC study reported here has investigated algal ponding systems as a 'core technology' in linking the treatment of both saline and sewage wastewaters, and providing for an integrated management of these wastes. Pretreatment before impoundment, economic pay-back in the form of high-value algal bio-products and upgradeability as communities move from essential service provision to industrial effluent treatment, provide specific targets in exploring the potential applications of algal ponding technologies.

4 A WRC STUDY IN INTEGRATED BENEFICIATION OF SALINE AND SANITATION WASTEWATERS

4.1 ALGAL PONDING SYSTEMS – A 'CORE TECHNOLOGY' APPROACH

Roobeek, (1995) has described biotechnology as a 'core technology', or an 'enabling technology', rationalising and energising developments in a range of associated fields. In a more constrained sense algal ponding systems have been investigated as a 'core technology', considering ponds and trenches as appropriate large-scale earth bioreactor vessels for environmental bioprocess development, and linking wastewater treatment and value recovery in the form of algal bio-products. Oswald (1995) has noted that ponds provide the most cost effective reactors for liquid waste management and the efficient capture of solar energy, enabling the reclamation of water, nutrients, and energy from organic wastes. Earthwork reactors, per unit volume, cost at least an order of magnitude less than alternative steel-reinforced concrete structures.

Although the application offers particular advantages for 'integrated wastewater resource management', particularly appropriate in the developing world context, potential for the approach need not be limited in this way. The linkage between ponding systems and algal biotechnology, as tools in the development of sustainable management of salinity and sanitation, has provided a principal research focus of the WRC study reported here.

4.2 WASTE STABILISATION PONDS AND WASTEWATER TREATMENT

Waste stabilisation ponds (WSP) have been constructed in a wide range of applications for the treatment of domestic and industrial wastewaters (Pearson 1996), including tannery effluents (Figure 4.1), and operate in most climatic zones of the world (De Pauw and Salamoni, 1991). The rapid development of the technology since the 1950s has been reviewed in detail by Mara and Marecos Do Monte (1987), and Mara *et al.* (1996). Early studies of these systems identified the role of microalgae in their successful operation (Gotaas and Oswald, 1954), and the High Rate Algal Ponding (HRAP) concept developed from attempts to optimise and intensify the function of the micro-algal components. The detailed theory of the HRAP has been reviewed by Shelef *et al.* (1980); Abeliovich (1986); Oswald (1988a&b) and De Pauw and Salamoni (1991), and mainly as applied to the treatment of domestic wastewaters.

In the HRAP, an association is established between high populations of algae and heterotrophic microorganisms, with photosynthetic oxygen production providing for the degradation of organics, and the algae, in turn, utilising the inorganic nutrients and CO_2 produced. While the advantages of the process were at first thought to be limited to this mutual microbial association, it was subsequently shown that the algal component also contributes significantly to the degradation of low molecular weight compounds, being responsible for up to 50% of the heterotrophic uptake of organics from the system (Abeliovich and Weissman, 1978; Abeliovich,1980&1986).

Figure 4.1. The Waste Stabilisation Pond evaporative disposal system treating tannery wastewaters at the Mossop-Western Leathers Co. Wellington. This unit was used as a model in the investigation of ponding systems reported in this study.

A polished effluent, suitable for discharge to the public water system is produced, following the removal, by settlement, of the algal-bacterial-zoogloeal detritus, the biomass termed ALBAZOD. The ALBAZOD from domestic wastewater treatment, however, has little value more than a cheap protein supplement, and the cost of its separation from the waste stream has been a negative factor (Soeder,1986). Overall yields can be around 150 tons.ha.$^{-1}$ year^{-1} dry weight, of which the algal component accounts for 60%. This is close to the theoretical photosynthetic productivity limits for the system (Oswald, 1988b).

The precise control of algal species in systems treating non-saline wastewaters is not possible, with wide fluctuations in type following shock loading, seasonal changes and variations in effluent content. Abeliovich (1986) has noted a trend in species dominance, dependant on organic load, with highly polluted water containing Euglena and Chlamydomonas, and in decreasing order of organic load Scenedesmus, Chlorella and Micractinium species. The standing algal crop can reach 1.0-1.5 g.L^{-1}dry wt. in the HRAP (Abeliovich,1980; Pearson *et al*., 1987).

Despite the above, Oswald (1988a) has described the HRAP as the most efficient way known to fix solar energy in the form of biomass. Soeder (1986) sees the HRAP, as applied to waste water treatment, offering the greatest potential of all microalgal biotechnologies to be exploited as a multi-purpose system. A number of other authors have drawn attention to the cost credits that are available where algal production is coupled to waste treatment. This can justify the use of otherwise expensive cell harvesting technology for the recovery of useful products (Benneman, *et al.*, 1980; Taiganides,1982). The incorporation of algal production into an already funded waste treatment process can deal decisively with the three factors that have been identified by Richmond (1986) as most limiting in the development of Algal Biotechnology – the costs of production media, construction of ponds and the harvesting and recovery of micro-algae.

4.3 ALGAL BIOTECHNOLOGY

Algal biotechnology had developed rapidly in the 1970s and 1980s, and the potential of aquatic photosynthetic production to deal with long-term resource replacement and sustained, environmentally sound economic growth, has been frequently identified (Hall,1986; Oswald, 1995). Photosynthesis is the most abundant energy storing process on earth, and the use of micro-algae (including cyanobacteria) for the industrial production of biomass, and speciality chemical products, has long been recognised, and has been the subject of extensive review (Shelef and Soeder,1980; Richmond,1986; Barclay and McIntosh,1986; Borowitzka and Borowitzka,1988; Lembi and Waaland,1988; Stadler *et al.*, 1988; Cresswell *et al.*, 1989).

Despite the enormous genetic potential of the microalgae, and the observation that they can produce nearly all the biological compounds currently obtained from conventional land crops, very few large-scale outdoor algal production systems have been successfully established (Richmond,1986). Dubinsky (1986) has made the point that the occasionally observed algal water bloom has been the "philosopher's stone" of applied algology, offering optimistic potential for pure culture which is difficult to reproduce under controlled conditions. Oswald (1988a) has noted that "there are no sustained axenic cultures out of doors in the real world."

With the possible exception of Chlorella and Scenedesmus cultivation as fresh water systems, the only really successful product-oriented outdoor algal biotechnology systems have been those where the exotic growth requirements of the algae in culture act as an environmental selection factor, ensuring the exclusion of competitors and the maintenance of a mono-species system. The two notable cases are the halophilic alga *Dunaliella salina*, which grows in strong brine solutions producing β-carotene and glycerol, and *Spirulina* sp. which grows best in meso-saline alkaline environments. *Spirulina* has a high-value market as a health food, as a feed additive in specialist aquaculture rations, and in the recovery of the pigments phycocyanin and phycoerythrin (Richmond,1986). The control of contamination and predation in algal cultures, in the absence of extreme culture conditions, has been identified as one of the major limitations to be overcome in the future development of algal biotechnology (De Pauw and Persoone,1988; Ben-Amotz and Avron,1989).

The selective action of salinity on aquatic populations is a well described ecological principle. Goldman and Horne (1983) have noted in saline lakes that as salinity increases there is a decrease in the diversity of organisms present, with an increase in productivity based on a few abundant species. In reviewing the current status and future prospects of algal biotechnology Richmond (1986) has identified saline systems as offering the most immediate potential to progress towards economically feasible processes. He has identified significant economic advantages in cultivating the halophilic algae as salt-tolerant crops, utilizing land and brackish water that is unsuitable for the production of conventional agricultural land crops. These conditions prevail widely in the developing world.

While food production in the form of microalgal biomass still suffers from the problems of low product values, which are common to other single cell protein (SCP) projects (Hall,1986), the biosynthesis of high-cost speciality products is likely to provide the 'research pull' on which future algal biotechnology will develop. In this regard, recent developments in microalgal genetic manipulation, based on the potential of saline algal culture systems, could offer future possibilities for the production of a range of economically significant metabolites, currently obtained from terrestrial plants, or from heterotrophic organisms cultured in expensive bioreactors (Richmond, 1986; Craig *et al.*, 1988).

Notwithstanding these developments Shelef (1987) had noted that despite a concerted phase of development in algal biotechnology, and the demonstration of the IAPS as among the most efficient wastewater treatment operations available, these systems had still not found widespread application.

4.4 'A BIOTECHNOLOGICAL APPROACH TO THE REMOVAL OF ORGANICS FROM SALINE EFFLUENTS' – PROJECT K5/410

The Rhodes University EBG was appointed by the WRC, in 1991, to undertake Project K5/410, 'A biotechnological approach to the removal of organics from saline effluents' as a one year study, to investigate the application of IAPS in the treatment, utilisation and ultimate disposal of saline wastewaters, and to report specifically on the potential for the development of algal biotechnology applications associated with these systems. Against the background of this apparent potential, it was also identified as an important objective of the study to investigate how far the concept could be pushed as both a 'core technology', and as a source of innovation within broader sustainability and 'integrated wastewater resource management' strategies. The project brief also called for proposals on the merits of a longer-term study into biotechnology-based approaches to the salinity problem.

The preliminary inquiry undertaken in Project K5/410 included both experimental and desktop study components, and the following findings were recorded:

- Algal biotechnology had made rapid advances, particularly in the 1970s and 1980s, and a basis for sustainable water resource management had been demonstrated with the identification of the technical potential for saline wastewater treatments available, at least theoretically, in the application of IAPS;
- Further sustainability potential was identified in terms of technical sustainability, as technology that lasts (low-construction costs, low-operator skills needs, reliability, flexibility and upgradeability); resource sustainability (potential to segregate saline wastes, 'closed system' operation; recovery of nutrients and resources, integrated resource management); economic sustainability (value adding opportunities in the form of potentially high-value bioproducts); social sustainability (service provision, job creation);
- While engineering design of algal ponding systems had reached an advanced stage at this time, principally as applied to sewage treatment, the concept needed to be subjected to a concerted process of 'technology-push' in order to adequately

demonstrate the viability of the potential linkages between wastewater treatment and value recovery in 'integrated wastewater resource management' approaches. Few commercially successful examples were available, and little had been reported on saline wastewater applications;

- IAPS appeared to offer advantages as appropriate technology in the developing world context, given low-cost, ease of operation and apparent flexibility in the range of possible wastewater treatment applications. Here also the technical possibilities needed to be pushed to demonstrate the wider applications potential, specifically in the context of saline wastewaters and sanitation. These systems appeared to offer potential for bioprocess development leading to improved treatment technology for saline wastewaters, and specifically related to pretreatments prior to the segregation of these wastes in saline water impoundments;
- Linkage between saline wastes and sanitation appeared to extend beyond the common use of a core IAPS technology for the treatment of a variety of different waste types. The potential for saline wastewater use in sewage reticulation to relieve pressure on freshwater resources, a disposal of sewage sludges in low-grade saline wastewaters, and also its use as a carbon source in the treatment of high-sulphate-saline wastewaters, such as AMD and tannery wastewaters, emerged from the study;
- In addition to salinity, the IAPS system offered opportunities for dealing with other priority sanitation pollution issues, especially in the development context, including nutrient enrichment and tertiary wastewater treatment, microbiological contamination and disinfection, removal of organic and inorganic pollutants, and especially heavy metal contamination.

It was evident that the choice of an appropriate model system was necessary in order to progress the above objectives, in a practical sense, and to subject the broad potential of the ideas to some form of critical examination. Tannery wastewater treatment appeared to provide certain of the key requirements for such a model. Apart from high organic loads, these wastewaters also contain both sodium chloride and sulphate salinities in high concentrations, a range of heavy metals, and numerous other organic and inorganic contaminants. Conventional WSP have been used in the treatment of tannery wastewaters and, in dealing with the saline component, have been operated as zero emission terminal evaporation ponding cascades (Shuttleworth, 1978; Rowswell *et al.*, 1984).

4.5 DEVELOPMENT OF THE WRC STUDY

The results of the K5/410 study led directly to two follow-up projects – Projects K5/495 and K5/651. The Project K5/495, with the same title as Project K5/410 ('A biotechnological approach to the removal of organics from saline effluents'), commenced in 1992 as a five-year follow-up study of the principle findings in K5/410.

The tannery system was used as a model ponding system for the investigation, which included a study of the microbial ecology of the tannery WSP at Mossop-Western Leathers Co. Wellington, South Africa. This showed the presence, at times, of massive micro-algal blooms of near monocultures of both *Spirulina* spp. and *Dunaliella salina* in the meso-saline and hyper-saline compartments, occurring across the well-established salinity gradients in these systems (Rose *et al.*,1996; Dunn 1998). Laboratory studies followed and showed the potential use of both species in the treatment of these complex wastewaters.

Apart from effective organic load reductions which were demonstrated in the algal-based treatments, enhanced micro-algal growth in the presence of organic substrates and the recovery potential for micro-algal biomass and β-carotene, as a fine chemical product, was demonstrated in the study (Laubscher, 1992; Rose, 1991, Rose and Cowan, 1992a; Rose *et al*.,1992; Maart, 1993).

The digestion of organic compounds occurring in the saline and hyper-saline anaerobic compartments of these systems was investigated and both efficient sulphate reduction, and also the removal of heavy metals from the water column, in the form of metal sulphide, and possibly also as carbonate and hydroxide precipitates, was demonstrated by Dunn (PhD1998). An enhancement in the hydrolysis of particulate organic carbon was observed in these studies and, given the high levels of sulphates in these wastewaters, the potential for follow-up investigation of biodesalination opportunities, using a range of complex organic carbon sources such as sewage sludges as the electron donor, was indicated (Laubscher, 1992; Rose *et al*.,1998; Molepane, 1999).

It was evident from the initial studies that development of 'closed system' and 'integrated wastewater resource management' applications, based on a process of environmental and algal biotechnology-driven innovation, was dependent on the development of an indigenous capacity with respect to the engineering requirements for the design, construction and operation of IAPS. Best studied at this time was the trade-marked Advanced Integrated Wastewater Ponding Systems (AIWPS), developed for domestic sewage treatment by Prof William Oswald in California, USA. Following a visit to California by the author, and then by WRC Research Manager Dr Oliver Hart, Prof Oswald was invited to visit South Africa in 1993. This led to the WRC Project K5/651: 'Appropriate low-cost sewage treatment using the advanced algal high rate oxidation pond', which commenced in 1994. This project undertook the technology transfer exercise, in collaboration with Prof Oswald and Dr Bailey Greene, both of UC Berkley, California, USA, whereby an AIWPS design was implemented in the construction of a demonstration and research plant in Grahamstown.

The research potential identified in the initial K5/410 feasibility study was followed up in 12 individual WRC research projects which were undertaken over the following period. The component projects which together have constituted the research programme 'Salinity Sanitation and Sustainability' are illustrated in Figure 4.2. The programme developed in four broad areas of activity: the investigation of meso-saline and hyper-saline systems, engineering applications of IAPS and the linkage of the sulphate-saline and sanitation wastewater systems. While these are the subject of separate individual reports (see Appendix 1), the principal developments are summarised below.

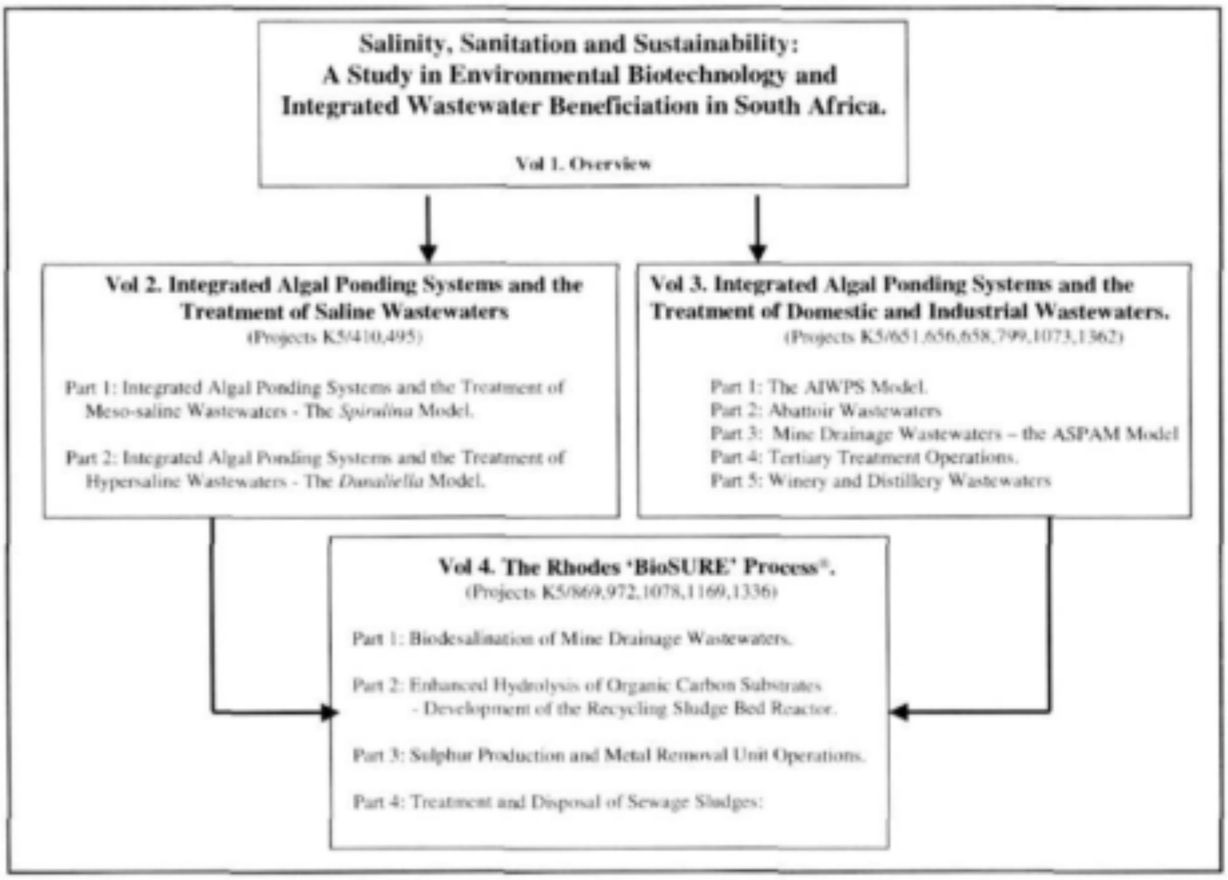


Figure 4.2. Research projects undertaken as components of the Water Research Commission Programme on 'Salinity, Sanitation and Sustainability'.

4.5.1 *Spirulina*-based Meso-saline Systems

Spirulina growth and biomass production in meso-saline wastewaters (< 40 $g.L^{-1}$ TDIS) was studied, and led to the development of an IAPS approach to their treatment. Scale-up application studies are reported for tannery effluent treatment systems. The development of the *Spirulina* HRAP (S-HRAP) is outlined and the construction of an industrial-scale plant is described, including commercial production of *Spirulina* biomass.

4.5.2 *Dunaliella*-based Hyper-saline Systems

The growth of *Dunaliella salina* in hyper-saline organic wastewaters (> 40 $g.L^{-1}$ TDIS) was studied and also led to the development of an IAPS approach in the treatment of these wastewaters. Studies in the stress physiology of this organism led to a patented Dual Stage Process for β-carotene production and the scale-up development and commercialisation of the process is described. The growth of *Dunaliella* in hyper-saline and alkaline solar evaporation ponding systems was investigated and led to developments of the *Dunaliella*-HRAP (D-HRAP) in the management of organic contamination in solar evaporite production.

4.5.3 Sulphate Salinity and Sanitation

The surprising observation of rapid solubilisation of particulate waste matter, and the enhanced hydrolysis of complex carbon substrates, observed in sulphate reducing ponding environments, led to a number of developments in what became known as the Rhodes

BioSURE Process® (WRC patent and trademark – Appendix 2). In one application of the process, sewage sludge was used as a carbon source to fuel sulphate reduction, and heavy metal removal, in a biodesalination process for the treatment of AMD wastewaters. The principles of the system have been applied to both active and passive AMD treatment operations. In another application the potential of the process in the effective degradation of particulate organic matter has also been investigated for the digestion and disposal of sewage sludges. In both cases technical-scale piloting of these developments is reported.

It was also shown that the hydrolysis of complex carbon substrates might be efficiently managed in the sulphate reducing compartments of ponding systems and that these may be so configured to enable the treatment of high sulphate and metaliferous wastewaters such as AMD in large-volume flows. These observations gave rise to the Algal Sulphate Reducing Ponding Process for Acid and Metal Wastewater Treatment (ASPAM) which is also described below.

Observations of stable sulphur biofilm formation on the tannery ponds, and studies in the microbial ecology of these systems led to the development of a sulphide oxidation sulphur recovery bioprocess. The ability to linearise the sulphur cycle with the removal of elemental sulphur (S^0) by biological action, and thereby effect the biodesalination of sulphate-saline wastewaters, provided the basis for an integrated bioprocess development approach.

Both of the above cases provided models for examining direct linkage of the saline and sanitation systems, and the implications for the 'closed system' sustainability approach.

4.5.4 Development and Engineering of IAPS Applications.

The practical requirements of process development, technology transfer and engineering scale-up and implementation formed a particular focus of the IAPS application studies undertaken. Demonstration and technical-scale pilot plants, and full-scale IAPS developments were constructed and evaluated in the following applications, and these studies are also reported below:

- IAPS and the S-HRAP for tannery wastewater treatment;
- An Oswald AIWPS for domestic sewage treatment;
- The Independent High Rate Algal Pond (I-HRAP) for tertiary water treatment, nutrient removal and raw water renovation;
- IAPS for abattoir wastewater treatment;
- The Rhodes BioSURE Process® for the treatment and disposal of sewage sludges;
- The Rhodes BioSURE Process® for the treatment of sulphate-saline gold mine wastewaters;
- The Rhodes BioSURE Process® for the treatment of sulphate-saline coal mine wastewaters;
- The D-HRAP and the biological management of solar evaporite production;
- Treatment of saline distillery and winery wastewaters.

4.6 TARGET GROUPS

While a strong water technology provision sector exists in some developing countries, such as South Africa, where delivery of high-tech solutions and major civil projects is routine, this capacity is not available everywhere. In addition there are particular sectors even in the developed world, such as small and medium-sized enterprises where high-cost, high-tech solutions are inappropriate, or cost ineffective. These, nevertheless, include key players in the development of sustainable practice. The IPWM White Paper notes the needs in empowerment and education to assist small, micro and medium enterprises (SMME) in particular, in developing appropriate integrated pollution and waste management procedures (DEAT, 2000). The following were identified as the target groups in this study:

4.6.1 Industry

The IPWM White Paper identifies the role that business and industry will play in enhancing integrated pollution and waste management performance by recognising the need to assist SMMEs in developing technical capacity, and appropriate integrated pollution and waste management procedures.

4.6.2 Intensive Peri-urban Agriculture and Agro-industry Business

A number of groups in this sector are relatively low-margin producers but, nevertheless, generate effluents seriously impacting on the environment. These include leather (tanning industry), meat (abattoirs), wine/fruit and vegetable producers (intensive agriculture) among others.

4.6.3 Rural and Village Communities and the Small Municipality

The IPWM White Paper recognises capacity will have to be built in marginalised and disadvantaged groups. In addition to the provision of water and sanitation services in the initial stages of development, small and micro-industrial activity will need to be provided for by upgrading wastewater treatment facilities as the commercial activities of a community develop. These groups may, at times, contribute high pollution loads to groundwater and diffuse runoff flows.

4.6.4 Mining and Power

The IPWM White Paper notes the need to interact with the mining and power generating industry regarding the investigation, promotion and implementation of waste minimisation and waste recycling practice.

4.7 CONCLUSIONS

An investigation of biotechnology-based potential for integration in the management of salinity and sanitation waste, as priority issues in the sustainability of both the bio-physical and human development environments, has resulted in the development of the WRC research programme reported here. Both integration and beneficiation, enabling value-addition in the waste treatment process, have been examined and algal ponding systems have been investigated as a 'core technology', and as a model system, in evaluating the feasibility of 'closed systems' production goals. The management of both meso-saline and hyper-saline wastewaters was investigated.

5 THE BIOTECHNOLOGY OF MESO-SALINE WASTEWATER TREATMENT: THE *SPIRULINA* MODEL

The problem of salinity, and the progressive salinisation of the public water system in South Africa, has been noted as one of the central issues affecting sustainability of the region's water resources. While prevention strategies, effected through system management and upstream process controls and changes, offer some potential for reducing salinity, the problem of saline pollution remains an intrinsic, and probably unavoidable, component of mining, power and fuel production, and including numerous other natural processes.

Clear limitations have been noted in the continued disposal of saline pollution by dilution in the public water system, and particularly in the inland regions of South Africa. Most saline wastewater streams contain additional contaminants, in one form or another, which require removal prior to desalination, segregation, and other forms of management. The treatment of organic saline wastes presents particular problems. The reduced solubility of oxygen in salt solutions, and a need for the selection of appropriate saline microbial populations, imposes severe constraints on conventional biological treatment processes. Treatment of organic saline wastewaters presents many unknowns in an area where few previous studies have been reported, and is likely to become an increasingly important issue where saline waters would be used for sewage disposal, in water-scarce areas. Dual pipeline systems using saline water are already in use in Australia (NDSP, 1999).

The WSP is one of the few cost-effective options which have been used for the treatment and final disposal of hyper-saline wastes, where dilution of the salt load into the public water system cannot be entertained (Rose *et al*., 1996). Despite the strategic significance of the technology in this application few studies are reported in the literature which deal, in any detail, with the meso-saline or hyper-saline WSP application. Nevertheless, the WSP has been used in a wide range of practical applications including the treatment of saline tannery wastewaters (Rowswell *et al*., 1984; Pearson 1996). The Rhodes University Leather Industries Research Institute (LIRI) had recommended their use by the Leather Industry in South Africa and a number have been constructed as zero discharge, terminal evaporation ponding cascades (Shuttleworth, 1978). Following observations of extensive algal blooms occurring in tannery WSP at times (Rowswell, pers.comm.), a number of preliminary studies were undertaken by the Rhodes University EBG, and these showed the presence of near mono-species cultures of *Spirulina* and *Dunaliella* occurring, at times, in intense blooms in different compartments of these evaporation ponding cascades.

The tannery WSP was chosen as a model system for the study of saline wastewater treatment for a number of reasons, including the following:

- The use of WSP is well-established technology for the treatment and disposal of high COD loads in wastewaters;
- In addition to high chemical oxygen demand (COD) loads, tannery effluents contain a range of pollutants including heavy metals and high levels of sulphates, ammonia, nitrates and protein nitrogen, providing, in some sense, a worst-case scenario of what may be encountered in saline wastewater impoundments;

- A wide salinity concentration gradient occurs across the evaporation cascades providing the sequential dominance of a range of different microalgal species;
- The engineering design of WSP is well established in the treatment of large wastewater volume flows. This provides a useful model for evaluating their application, as appropriate bioreactors, for the treatment of saline wastewater streams such as mine drainage wastewaters;
- The low-cost, and quasi-passive nature of WSP, makes for sustainability where it is anticipated that treatment of wastewaters flows will stretch over long periods of time.

5.1 AIMS

The specific research aims of the Project K5/495 "A biotechnological approach to the removal of organics from saline effluents" were identified as follows:

- Development of a saline HRAP process for removal of organics from saline wastewaters;
- Optimising the operation of the solar evaporation WSP process by the manipulation of micro-algal production;
- Demonstration of a utility value for saline wastewaters with the recovery of value in the form of micro-algal bioproducts;
- Removal of heavy metals from saline wastewaters;
- Application of membrane separation techniques employed for the harvesting of micro-algal biomass and the recovery of bio-products.

5.2 RESULTS

This study is the subject of the WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Saline Wastewaters. Part 1 – Meso-saline Wastewaters: The *Spirulina* Model'. The main findings of this study are summarised here.

5.2.1 The Microbial Ecology of Saline Waste Stabilisation Ponds

The investigation commenced with a detailed study of the microbial ecology of the saline WSP in use at Mossop-Western Leathers Co. at Wellington, South Africa (Figure 4.1 and 5.1).

These studies have been reported by Rose (1991), Rose *et al*.,(1992), and Dunn (PhD, 1998).

Performance across the WSP shows reductions in COD, ammonia and phosphates, associated with increases in alkalinity, TDIS, dissolved oxygen (DO) and chlorophyll-a across the system. The dark brown to grey colour of the raw tannery effluent changes to a bright pink to dark purple in the anaerobic Ponds 1 to 5, providing an indication of the changing dominance of the microbial populations. These ponds are dominated by large populations of purple sulphur bacteria, various *Chromatium* spp., and purple non-sulphur bacteria including *Rhodobacterium* spp. Green sulphur bacteria of *Chlorobium* spp. occur in smaller numbers with the occasional observation of *Dunaliella viridis*, depending on season. Bacterial photosynthesis and lithotrophic metabolism result in the oxidation of sulphide at the pond surface which manifests as an extensive biofilm of white So and, at times, may blow into thick windrows against the pond levees.

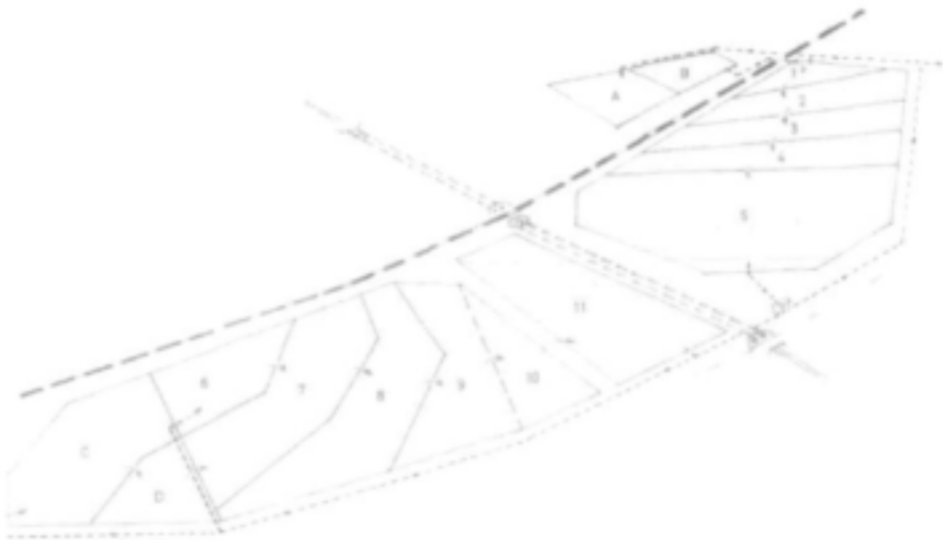


Figure 5.1. Plan diagram of the Waste Stabilisation Pond tannery wastewater treatment operation at Mossop-Western Leathers Co. tannery in Wellington. The effluent treatment path in this zero discharge evaporation ponding cascade flows from Pond A through Pond 5, and from the collection sump to Pond C through Pond11.

In Pond 6 the colour changes to dark green due to the blooming, at times, of near monocultures of the cyanobacterium *Spirulina*. The particular strain which dominates in this system is morphologically distinct, it has been provisionally identified as *Spirulina platensis*. Massive blooms of this organism occur and large rafts of biomass drift on the surface, and also accumulate on the pond levees. As the salinity rises through Ponds 9 and 10, numbers of *Spirulina* decrease and small mixed blooms of the halophilic chlorophytes *Dunaliella salina* and *Dunaliella viridis* occur. Despite the colour change *Rhodobacterium* spp. remain the dominant component of the bacterial population in the latter ponds, and their cell numbers ($6.4x104.mL^{-1}$) do not change significantly.

In addition to the quite dramatic differentiation in microbial ecology evident across the rising salinity and nutrient gradients occurring over the pond cascade, water column studies in each pond also showed a very clear stratification into surface aerobic, subsurface anaerobic and bottom sludge zones. The extent of the surface aerobic layer varied from only a few millimetres, in the anaerobic ponds, and supported mainly sulphide oxidizing bacteria, and up to a metre or more in aerobic ponds overlayed by a cap of micro-algal growth. In ponds undisturbed by prevailing wind activity, a complete functional biological sulphur cycle or sulphuretum was demonstrated. Sulphide increased by up to 88% down the water column and sulphates showed a corresponding increase in the aerobic surface layers. Ammonia concentrations increased by about 10% down the water column.

These ponding systems are characterised by severe odour nuisance associated with sulphide and ammonia production, and probably also mercaptans produced in the degradation of the proteinaceous wastes. Odours are carried by prevailing winds into the residential areas of Wellington, and given a level of conflict between the tannery and the local community, the town has become colloquially known in the area as 'Smellington'. It was noted that where algal blooms establish on the surface of ponds very little odour release occurs. This gave rise to an additional project objective where manipulation of the system to achieve a capping of the anaerobic ponds with micro-algal growth would be investigated as a possible mechanism for the control of odour release in these systems.

5.2.2 Photosynthetic Productivity and Nutritional Studies

Given the reliability of *Spirulina* occurrence in the WSP, observed over many years, its use in the development of an IAPS treatment approach for tannery effluents formed the principal focus of the subsequent study.

The photosynthetic productivity of the ponding system was estimated on the basis of carbon fixation values recorded in ponds over the various seasons. While mid-summer fixation rates approached 15 $gC.m^{-2}.day^{-1}$, which is in the upper range reported for fully optimised sewage HRAP (Oswald, 1995), winter values fell to about 4 $gC.m^{-2}.day^{-1}$, providing an annual average production of around 7.5 $gC.m^{-2}.day^{-1}$. Richmond (1986) has reported experimental yields for *Spirulina* of up to 30 $gC.m^{-2}.day^{-1}$, while the average values recorded here compare favourably with the 8-12 $gC.m^{-2}.day^{-1}$ reported for outdoor culture basins by Fox (1988).

It is thus apparent that total *Spirulina* production through the facultative component of the WSP system may generate about 110 $ton.year^{-1}$ biomass over a 13 ha pond system. This translates into an estimated oxygen production in the system of around 165 tons $O_2.year^{-1}$, or a solar energy conversion equivalent to mechanical oxygenation of 165 000 kW hrs (calculation based on Oswald, 1988b). Given elevation of oxygen mass transfer barriers due to the salinity of the system, expenditure of mechanical energy to achieve this level of oxygen actually transferred would be substantially higher than this figure. The direct diffusion of photosynthetically produced oxygen, between the micro-algae and bacterial consortia in these systems, also offers additional efficiencies in mass transfer.

The nutrient status of the tannery effluent feed to the WSP, and it's capacity to sustain *Spirulina* growth through the phases of pond treatment, was evaluated on the basis of the algal biomass and oxygen release potential method described by Oswald (1988b). An analysis of the major elements present in the effluent during the various stages of the ponding cascade was compared to Zarrouk's defined inorganic medium and, while highlighting some imbalances in the C:N:P ratio of the tannery effluent, provided an indication of its suitability as a growth medium for *Spirulina* culture.

It was thus quite surprising that nutritional studies, comparing growth of the Wellington *Spirulina* isolate in defined inorganic and organic pond-derived media, showed substantially higher biomass production in the tannery wastewaters. The potential heterotrophic supplementation of a phototrophic lifestyle was provisionally demonstrated in D-[^{14}C]-glucose radio labeled nutrient uptake studies.

In addition to the COD load reductions demonstrated in flask studies for *Spirulina*-tannery effluent mixtures, the addition of bicarbonate was shown to extend the ammonia toxicity range. This provided an indication that *Spirulina* growth in the first ponds, receiving a high protein raw effluent, could be manipulated by the recirculation of alkaline water from the latter ponds, and that induction of micro-algal capping could enable odour control in the anaerobic ponds. These results provided experimental support for the observations, first made in 1958 by Abbott in Cape Town (Pescod, 1996), that recirculation of algae-rich waters substantially improved pond performance, and achieved odour control in WSP systems.

The above studies provided the first provisional indication that a S-HRAP could be conceived to function as a separate unit operation in tannery effluent treatment. They also showed that selective cultivation of the *Spirulina* biomass, particularly on the surface of the anaerobic compartments, could provide an appropriate methodology for improved odour control and operation of the tannery effluent WSP treatment system.

5.2.3 The *Spirulina* HRAP – A Unit Operation in Tannery Effluent Treatment

Following the flask studies reported above, the performance of the *Spirulina*/tannery effluent treatment operation was investigated in 5L photobioreactor studies (New Brunswick Bioflow III), in both batch and continuous mode operation. Figure 5.2 reports typical COD and ammonia reduction in a batch-fed sequence with a tannery effluent loading rate equivalent to 5% reactor volume.day $^{-1}$.

Based on the photobioreactor studies, a scale-up evaluation of the *Spirulina* treatment process was undertaken in an HRAP pilot plant consisting of two 80 m^2 ponds, constructed on-site at the Mossop-Western Leathers Co. tannery, in Wellington (Figure 5.3). Effluent feed to these ponds followed partial treatment through the primary facultative pond (PFP) A (Figure 5.1), and they were seeded with *Spirulina* biomass sourced from the tannery's WSP system.

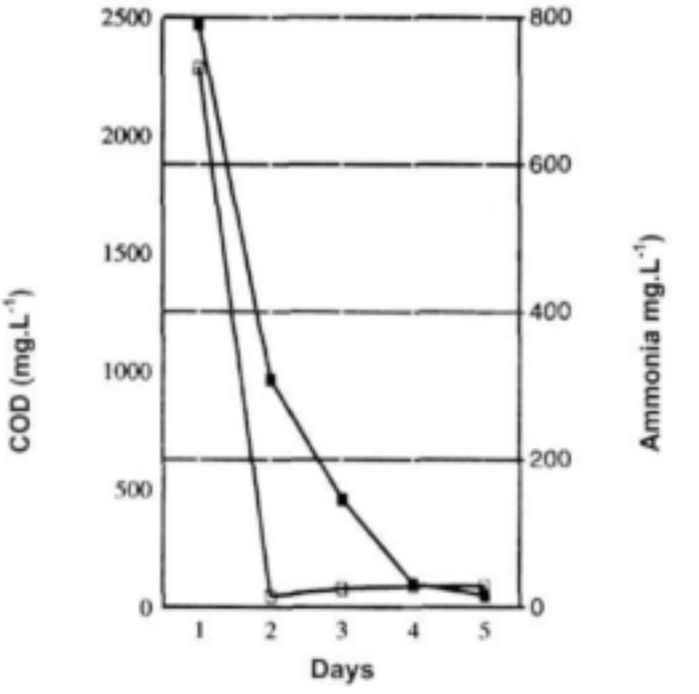


Figure. 5.2. COD and ammonia removal in a *Spirulina* photobioreactor showing a typical 5-day batch fed sequence with a tannery effluent loading rate equivalent to 5% reactor volume.day^{-1}. (Closed square=COD; open square=ammonia).

The pilot HRAP were operated in batch-fed continuous culture mode, and optimised performance gave organic load reductions of 85% at a loading rate of 7%.day^{-1} pond volume, and ammonia reductions of 93% at a loading rate of 8%.day^{-1} pond volume. Biomass increased by nearly 5% day^{-1} in this mode of operation. The pilot system performed best at operating depths around 15cm, and a linear flow velocity of 18 cm.sec^{-1} proved to be optimal. Ammonia toxicity, above 60-80 , proved to be a major limiting factor in the HRAP. However, recirculation studies usinmg.L^{-1}g alkaline waters from the terminal ponds showed that the ammonia toxicity threshold may indeed be elevated in this way, as indicated in the earlier flask and bioreactor studies. Alkaline stripping of ammonia, which at times reached 800 mg.L^{-1} in these effluents, is thought to be the principal mechanism involved here.

Photosynthetic productivity in the pilot HRAP averaged 5.03 gC.m^{-2}.day^{-1} over summer and winter operating conditions, which was somewhat lower than the 7.48 gC.m^{-2}.day^{-1} average recorded for *Spirulina* blooms in the WSP (Dunn, 1998). At a dry mass equivalent of around 9.0 g dry matter.m^{-2}.day^{-1}, this was well below the 15.0-20.0 g dry matter.m^{-2}.day^{-1} reported by Oswald (1988a) for sewage HRAP. However, the yields established in this study do compare well with the 7.30-9.50 g dry matter.m^{-2}.day^{-1} reported by Saxena *et al.*,(1983) for summer conditions, which fall to 5000 mg dry matter.m^{-2}.day^{-1} in winter. While WSP surface water temperatures may vary by no more than 5-8°C over the seasons at the Wellington site, incident light, measured as photosynthetically available radiation at noon, will vary between 500 and 1300 moles.m^{-2}.sec^{-1} from winter to summer conditions, which influences total photosynthetic production levels achieved.

Figure 5.3. The *Spirulina*-HRAP pilot plant at Mossop-Western Leathers Co., Wellington, showing one of the 80 m^2 High Rate Algal Ponds.

5.2.4 The Full-scale *Spirulina* HRAP

Following the demonstration of process capability in the technical-scale pilot plant studies, Mossop-Western Leathers Co. undertook a commercial feasibility study of the IAPS process, and followed this with the practical implementation of the system. This involved the retrofitting of the anaerobic pond A (Figure 5.1) to function as a primary facultative pond, and also the construction of a full-scale HRAP.

A 2500 m^2 paddle wheel-driven HRAP (Figure 5.4) was designed following criteria described by Oswald (1988b), to undertake an approximate 30-fold scale-up of the pilot plant. The unit was constructed adjacent to the existing Pond 1, and was designed to treat 25% of the tannery's total effluent flow of 450 $m^3.day^{-1}$. Pipework enabled the HRAP to receive partly treated effluent from the primary anaerobic ponds A/B in this system and thus facilitated its evaluation either as a component of the normal WSP cascade flow path, or as a stand-alone effluent treatment unit operation. An operating depth of 30 cm, and linear flow velocity of 20 $cm.sec^{-1}$, were found to be optimal. The HRAP was seeded with *Spirulina* biomass from the WSP.

The S-HRAP was operated at increasing effluent loading rates from the PFP, commencing at 3% $.day^{-1}$ through 15%$.day^{-1}$. Stable operating conditions could be sustained at a maximum loading rate of around 10% HRAP volume$.day^{-1}$, enabling reductions in COD of 78%, ammonia 94%, sulphides 99% and phosphates 92% (Table 5.1). This is nearly double the optimum loading previously achieved, and the increased surface area could account for the improvement in performance compared with the photobioreactor and pilot HRAP studies. The quality of effluent treatment recorded in the 2500 m^2 HRAP exceeded that achieved in the 13 ha of the WSP cascade receiving the same effluent type.

In a separate study the quality of the S-HRAP-treated effluent was shown to be suitable for return to the tannery for use in certain production operations, thereby achieving a substantial improvement in the WSP water balance.

Figure 5.4. The 2500 m^2 *Spirulina*-HRAP constructed as a component unit operation in the full-scale IAPS treating tannery wastewaters at Mossop-Western Leathers Co., Wellington.

Following the establishment of the HRAP unit at the beginning of the cascade, and the implementation of recirculation practice, it proved possible to establish an aerobic capping of the previously anaerobic ponds. This operation demonstrated the practical efficiency of the HRAP and algal capping in achieving substantial reductions in odour generated by the WSP system.

Table 5.1. Effluent treatment performance (as % change) in the 2500m^2 *Spirulina*-HRAP fed primary facultative pond pre-treated tannery effluent at a 10% daily volumetric loading rate. Standard deviation in brackets.

	Tannery Effluent	Primary Fac. Pond	HRAP	HRAP Step	Combined Treatment
pH	8.17(0.06)	8.3(0.7)	8.98(0.57)	+8%	+9%
COD (mg.L^{-1})	2472(1810)	1722(325)	539(147)	-69%	-78%
Ammonia (mg.L^{-1})	731(98)	764(93)	42(32)	-95%	-94%
Sulphide (mg.L^{-1})	285(422)	993(90)	1.3(5.2)	-99%	-99%
Sulphate (mg.L^{-1})	975(788)	<1	1097(150)	+99%	+99%
Phosphate (mg.L^{-1})	19(12)	7(1)	1.5(0.33)	-27%	-92%
Suspended Solids (mg.L^{-1})	243(196)	434(67)	0.1(0.29)	-99%	-99%

5.2.5 Sulphate Reduction and Metal Removal Studies

Observations of active sulphate reduction occurring in the pond water column led to a more detailed investigation of the performance of the primary facultative pond. Relatively poor performance in this unit, and chronic accumulation of solids, had been corrected by the establishment of facultative operation with the installation of surface aerators and the location of the inlet pipe to the base of the pond (Figure 5.5). In this way a clear oxypause was established around 1.5m below the surface, with active anaerobic activity taking place below this level. High levels of sulphate reduction were recorded in the anaerobic zone and accounted for metal removal within the system in the form of metal sulphide, carbonate or hydroxide precipitates. More surprising, however, was the efficiency of particulate matter degradation, and the high level of suspended solids removal accomplished in the sulphate reducing zone of the reconfigured primary facultative pond. The results are reported in Table 5.2 which shows the performance of a complete sulphur cycle, or sulphuretum, operating in this unit.

Table 5.2. *Performance of the Primary Facultative Pond and High Rate Algal Pond treating tannery effluent* showing sulphate reduction, sulphide oxidation and COD removal through the various stages of the process.

	Tannery effluent	Facultative pond anaerobic compartment	Facultative pond aerobic cap	HRAP
Sulphate as SO_4^{2-} (mg.L^{-1})	975	<1	989	809
Sulphide as Na_2S (mg.L^{-1})	285	1100	76.5	0.1
COD (mg.L^{-1})	2474	1216	1216	394
Suspended Solids (mg.L^{-1})	243	0.5	0.5	1.3

The observations in this study relating to the apparently efficient use of complex organic carbon in sulphate reducing systems, and the surprising reduction in particulate organic material, led to follow-up studies using, first, tannery effluent and then sewage sludges and other complex organic substrates as carbon sources for sulphate reduction. Applications of these findings to the treatment of high sulphate metal containing AMD wastewaters, and the use of sulphate-saline wastewaters for the disposal of primary sewage sludge (PSS) became the subject of a separate investigation, and these studies, resulting in the development of the Rhodes BioSURE Process®, are reported.

Metal binding by algal biomass in the ponding system presented a potential problem, especially where biomass recovery and use were to be contemplated. It was shown in this study that the problem could be overcome by appropriate management of the PFP, with metal precipitation effected in this unit. However, the potential for biomass produced in these systems to be recovered and used as a reagent in metal removal from industrial wastewaters was also examined. It was found that both *Spirulina* and *Dunaliella* could be manipulated to remove a range of metals from solution, by bio-absorption, by uptake mechanisms, and also by photosynthetic elevation of the medium pH. These studies have been reported by Boshoff (PhD,1998).

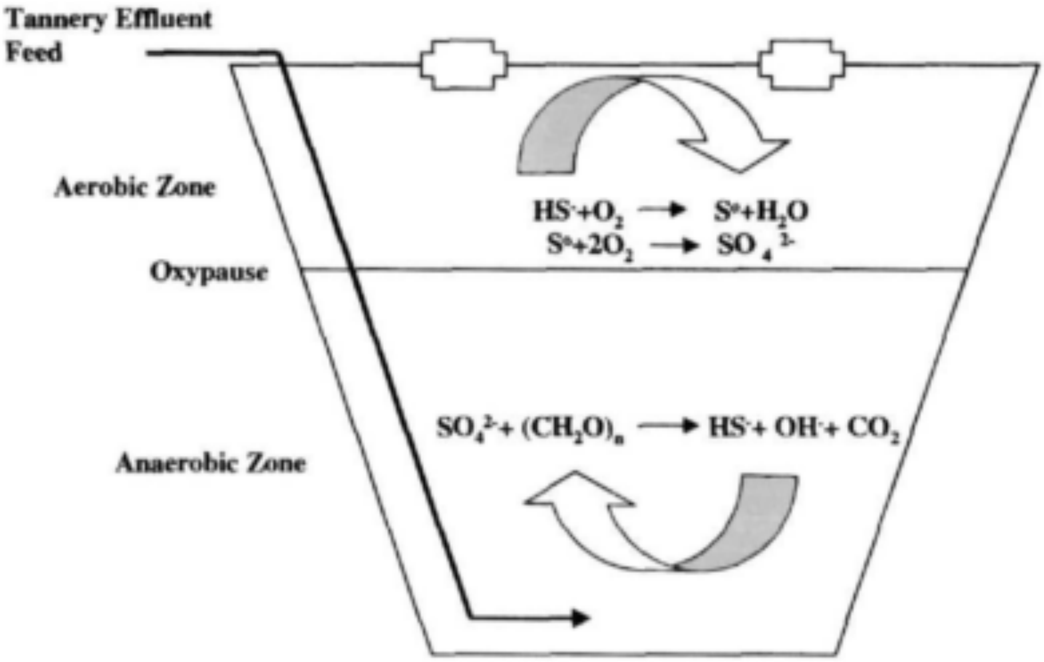


Figure 5.5. The primary facultative pond of the IAPS system treating tannery wastewaters after reconfiguration, using surface aerators in establishing a stable oxypause, and relocating feed inlet to the bottom of the pond.

5.2.6 *Spirulina* Biomass Harvesting

Spirulina biomass is a high-value additive in animal and aquaculture rations, and is also used as a human health food supplement. Many of the fatty acids occurring in fish oils are derived ultimately from micro-algae via the food web. Given the potential *Spirulina* biomass productivity demonstrated for the system, an investigation of the feed value of the biomass was undertaken by Maart (MSc, 1993) using material harvested directly from the ponds. Both falling-screen plankton net harvesters, and cross-flow microfiltration membrane systems, were evaluated for harvesting of biomass from the ponds (Rose *et al.*,1992). Toxicological studies were undertaken using Artemia bioassays, and also feeding trials in new-born chicks.

Histopathology studies showed no adverse effects in the feeding group, and nucleic acid and pesticide residues were found to be within prescribed levels. Where biomass was harvested following the reconfigured PFP, heavy metal levels were substantially reduced, and also complied with aquaculture nutritional standard requirements.

The use of the harvested biomass in feed rations for the rainbow trout Onchorhynchus mykiss was demonstrated, with *Spirulina* supplementation enabling partial replacement of fishmeal ration components, and also resulting in clearly enhanced colouration of the skin and flesh of the cultivated fish. In addition to growth studies, toxicological acceptability was again demonstrated by histopathological studies in reared fish. The biomass was also used in the development, by the Rhodes University Ichthyology Department, of a novel feed formulation for the cultivation of the South African abalone *Haliotis midae* (Britz, 1996). The resulting 'Abfeed' product is now widely used in the commercial production of abalone (Figure 5.6).

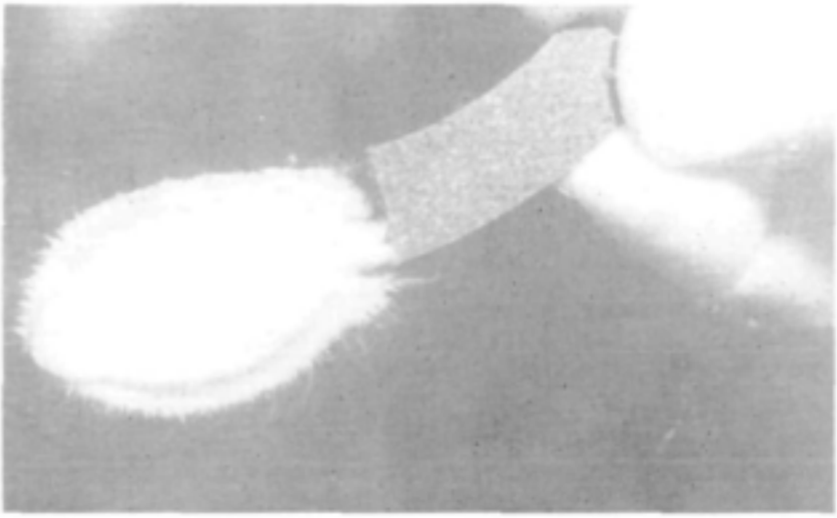


Figure 5.6. A young abalone *Haliotis midae* grazing on the 'Abfeed' ration, including *Spirulina* biomass harvested from the Wellington ponds.

While blooms of *Dunaliella* were confined mainly to the hyper-saline ponds at the end of the WSP evaporation cascade, and did not play any meaningful role in the primary effluent stream, the development of their use in the treatment of hyper-saline organic wastewaters was investigated and demonstrated in studies reported by Laubscher (MSc, 1992). This application in hyper-saline wastewater treatment will be discussed in greater detail below. It was also shown that Rhodobacterial blooms occurring in the ponds may be harvested by membrane ultrafiltration methods, and will yield significant amounts of vitamin B12.

5.3 CONCLUSIONS

The study demonstrated the potential performance of IAPS as an effective treatment system for tannery wastewaters. In addition to the HRAP, as a potentially free-standing unit operation in effluent treatment, the role of micro-algal production in an IAPS configuration, including both the optimised PFP and S-HRAP units, was also demonstrated. Wastewater treatment performance was substantially better than that achieved in the conventional WSP, occupying about 10% of the footprint area. The final configuration of the IAPS treatment system is illustrated in Figure 5.7.

Incorporation of the IAPS into the operation of the existing WSP system at Wellington offered additional advantages in the recovery of a treated water stream of sufficiently high quality to be recycled to certain process operations. Also, capping of the anaerobic ponds achieved an effective odour control in the WSP system. In this regard it was shown that the S-HRAP may also be used as a free-standing unit operation, retrofitted to an existing problematic WSP purely for purposes of odour control. In addition to the effluent treatment application, commercial potential of biomass harvested from the system may be based on an estimated dry weight production of around 10 $ton.ha^{-1}.year^{-1}$. Harvesting of *Spirulina* biomass in this system is currently (2002) being commercialised and dried biomass is being sold for use in animal and aquaculture feed rations.

The industrial IAPS plant development at Mossop-Western Leathers Co., Wellington, was officially opened by the Hon. Minister of Water Affairs and Forestry, Prof Kader Asmal, on 28 November, 1997.

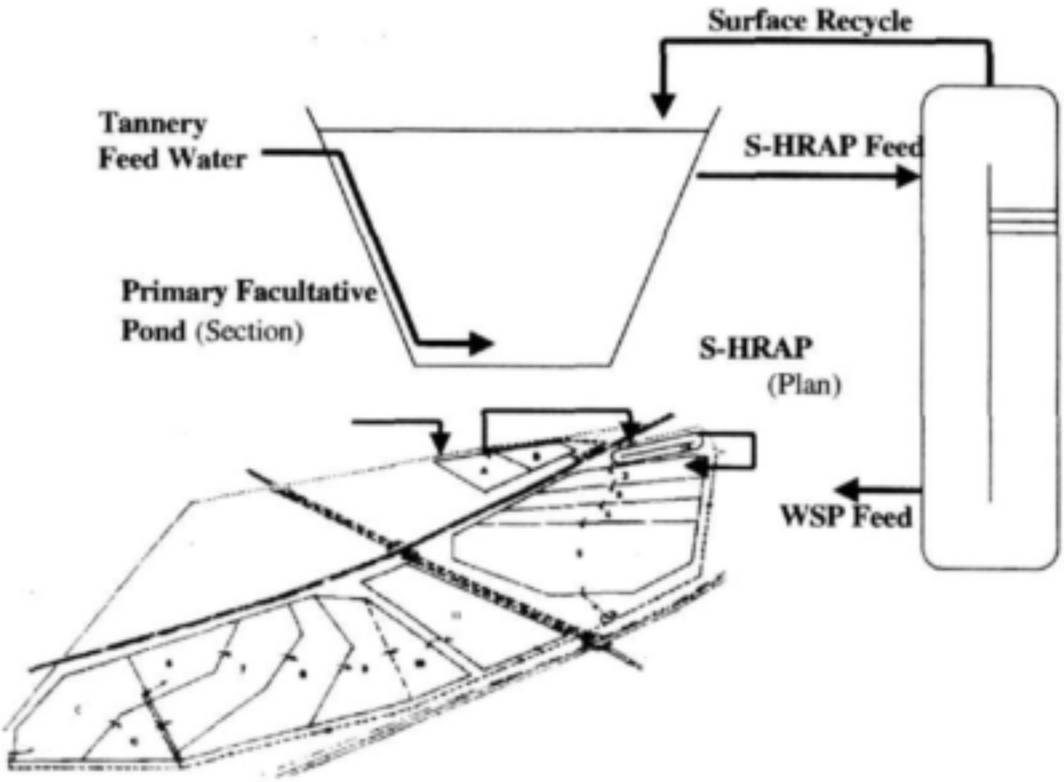


Figure 5.7. An IAPS configuration of a Waste Stabilisation Ponding system for the treatment of tannery wastewaters based on the Wellington developments. Feedwater to the system passes into the anaerobic compartment at the base of the Primary Facultative Pond and to the surface which may be overlaid with oxygen producing algal waters or fitted with surface aerators. Partially treated water then passes through the *Spirulina*-HRAP (S-HRAP) to the Waste Stabilisation Pond cascade where the algal overlay controls odour release.

The tannery IAPS study also led to a number of technology transfer exercises which resulted in its evaluation in associated wastewater treatment applications. The observations of particulate organic carbon hydrolysis in the sulphate reducing compartments of the IAPS, and their apparently efficient use as carbon sources in sulphate reduction, led to studies on the linkage of AMD treatment and PSS disposal. These bioprocess development studies followed as separate WRC projects, and the findings are described below.

It was apparent from the tannery study that IAPS systems may offer opportunities for a more general approach to saline wastewater treatment. Also, in terms of salinisation problems and the associated threats from this source to the sustainability of the national water resource, ongoing dilution practices may not present the only options in the continued management of saline wastewaters. The ability to remove pollutants from saline waste streams may be developed to enable their impoundment in artificial wetlands without threat to the wildlife which would inhabit them. The demonstration of a utility value for these wastes, and the recovery of value in the form of bioproducts and recycled water usage, together with potential employment creating opportunities, provide a departure point for follow-up evaluations of 'closed system' and 'integrated wastewater resource management' approaches in the treatment and disposal of saline wastes.

6 THE BIOTECHNOLOGY OF HYPER-SALINE WASTEWATER TREATMENT: THE *DUNALIELLA* MODEL

While saline wastes are produced quite widely in industry, and a surprisingly high percentage of these may be segregated into low-volume, concentrated saline streams by the application of effective process and good housekeeping practices (DWAF, 1989a), these are nevertheless largely disposed of, by one route or another, via dilution into the public water system. The impact of rising salinisation on the sustainability of the water resource in Southern Africa has already been noted.

Where desalination techniques are able to be used, pretreatment is often needed to remove contaminating organic materials and salts causing occlusion and scaling effects, particularly in membrane-based desalination systems. Notwithstanding the above, the actual implementation of desalination practices may be constrained, quite simply, by the lack of facilities for the management of the brine concentrates produced (Buckley *et al.*, 1987).

This study developed from the observations of intermittent blooms of *Dunaliella*, a halophilic green alga, in hyper-saline compartments of the tannery WSP (Rose, 1991). In addition to an evaluation of the IAPS for the treatment of hyper-saline organic wastewaters, similar in concept to the S-HRAP development, potential for the linked production of β-carotene to add value to brine treatment, was also considered.

The objectives underpinning the development of a *Dunaliella*-based IAPS treatment for hyper-saline wastewaters included the application of pre-treatments required to remove organics, heavy metals and possibly other contaminants prior to desalination processes, or disposal of concentrates to saline water impoundments. The demonstration of a utility value for these wastewaters would offer a mechanism for a 'closed system' approach to the problem.

6.1 AIMS

This study formed a component of Project K5/495, 'A biotechnological approach to the removal of organics from saline effluents', and, in dealing with issues related specifically to hyper-saline streams, addressed the principle objectives of the project:

- ❑ Development of a saline HRAP process for removal of organics from saline wastewaters;
- ❑ Optimising the operation of the solar evaporation WSP process by the manipulation of micro-algal production;
- ❑ Demonstration of a utility value for saline wastewaters with the recovery of value in the form of micro-algal bioproducts;
- ❑ Application of membrane separation techniques employed for the harvesting of micro-algal biomass and the recovery of bioproducts.

Although the objectives relating to metal removal were reported in the previous chapter, these findings relate equally to hyper-saline wastewaters.

The studies reported here focussed on three broad areas:

- The growth of *Dunaliella* in tannery effluent WSP systems, the removal of organics and nutrients, together with β-carotene and glycerol production;
- The production of β-carotene in hyper-saline sodium chloride brines;
- Growth and performance of *Dunaliella* in hyper-saline carbonate brines, both as a causative agent and as a solution to the problem of organics in solar evaporite production.

6.2 RESULTS

This study is the subject of the WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Saline Wastewaters. Part 2 – Hyper-saline Wastewaters: The *Dunaliella* Model'. The main findings of this study are summarised here.

6.2.1 Hyper-saline Organic Wastewaters and the *Dunaliella* HRAP

The growth performance of *Dunaliella salina* (CCAP 19/30 – Bardawil strain) was evaluated in a range of different effluent streams generated by tanneries, and these studies have been reported by Laubscher (1992). It was shown that hide soak liquors, generated in the process of rehydrating salt-cured hides, consistently provided the most favourable growth medium of the various effluent streams examined. The observation was again made that algal cell growth yields in the organic saline media outperformed production in defined inorganic growth media developed specifically for the cultivation of this organism. As was the case in the *Spirulina* study, this was a surprising result for an apparently obligate phototrophic organism growing in the light. The algal treatment was accompanied by substantial organic load reductions in the effluent (Rose, 1991).

Glycerol production by the *Dunaliella* cell, as an osmoticant enabling its growth over a wide salinity concentration gradient, has been described by Ben Amotz and Avron (1980). *The results noted above suggested the need to investigate its production in the D-HRAP*, as a co-metabolite, possibly contributing to the performance of the organic hyper-saline HRAP. The stimulation of microbial activity in the algal-bacterial co-culture could contribute to the efficient breakdown of complex organic compounds observed in the treated effluent.

The study of glycerol production, in a range of 15 *Dunaliella* species grown in saline tannery wastewaters, has been reported by Emmett (MSc, 1996). She showed an optimal glycerol production of around 16 $g.m^{-2}.day^{-1}$ in flask studies, which is considerably higher than the sustained production of 4.5 $g.m^{-2}.day^{-1}$ reported for defined inorganic media. Using a series of flask studies it was shown that the amino acid glycine, present in high concentrations in hide tissues, was associated with the induction of glycerol release by *Dunaliella* growing in tannery effluent media. The effect was further demonstrated in studies using radio labelled amino acid uptake in defined media cultures. Detailed studies on the growth of Bacillus megaterium in the glycerol-tannery effluent medium demonstrated enhanced bacterial cell growth for the mixed system, compared to conventional growth media. In a separate study, Rose (1991) had shown uptake and internalisation of bovine serum albumin in radio labelled studies of *Dunaliella* grown in tannery effluent.

While *Dunaliella* cultures yielded bright green luxuriant growth when cultivated in the organic medium, β-carotene production was found to be extremely low under these conditions. Nevertheless, it was shown that when cells (CCAP 19/30) were transferred to a nitrogen deficient stress medium, β-carotene production was induced, and accumulated to levels equivalent to around 10% cell mass. It was found, unexpectedly, that the higher the organic strength of the original growth medium, the higher the production of β-carotene.cell^{-1}, when cells were transferred into the nitrogen deficient stress medium. Optimum β-carotene yields averaged around 100 pg.cell^{-1} in the stress stage of the system.

Although this investigation was confined to laboratory flask studies, the results provided a provisional indication that a *Dunaliella*-based HRAP process, for the treatment of hyper-saline organic wastewaters, would be worth further evaluation as a scale-up exercise, similar to that undertaken for the *Spirulina* system. However, this potential application was not followed up, given overall focus in the EBG at that time on the second observation arising from the study. This related to the enhancement of β-carotene production in hyper-saline media by the manipulation of the physiological stress responses in *Dunaliella*.

6.2.2 The Dual Stage Process for β-carotene Production

Fluorescence induction stress response studies reported by Rose (1991), had indicated a possible role for the 'plant hormone' abscisic acid in mediating the stress response cascade in *Dunaliella salina* (Cowan and Rose, 1991 a&b; Cowan *et al.*,1992). The induction of β-carotene hyper-accumulation in the cell had been observed to occur through a number of clearly defined stages, resulting in physiological commitment by the cell to a process in which the compound accumulated up to 10%-14% cell mass. The β-carotene accumulation response was poor where the organism grew at logarithmic growth rates, in optimal growth media, but well developed under stress conditions. It was suggested that a Dual Stage Process (DSP) could be operated, where cells from an initial biomass production growth stage would be separated and then transferred to a second stage, where β-carotene production would be optimised by manipulating the organism's stress response physiology. This should in theory provide better overall β-carotene yields than a single stage averaging operation, where neither cell growth nor β-carotene production were fully optimised (Rose, 1992a). Experimental studies confirmed these observations and the DSP development was patented by the WRC (Rose and Cowan, 1992b).

The DSP for β-carotene production was the subject of a number of detailed follow-up studies by Phillips T (PhD, 1994), Logie (PhD, 1995) and Phillips L (PhD, 1995), and resulted in a commercialisation of the process undertaken by Sasol Co. The main points of this study are summarised below, and the separate work of the Phillips' is noted by use of their initials.

Phillips T (1994) undertook the comprehensive evaluation of a range of stress factors which might be manipulated in the management of β-carotene accumulation in D. salina (CCAP 19/30), including salinity, nutrient, light and pH effects. He showed that, although interactions of these factors each played a role, high light intensity was the single most important factor in the β-carotene hyperaccumulation response in this organism. He noted a relationship between the extent of the photoinhibitory response, and the amount of β-carotene accumulated, and also that the response occurred in two clearly differentiated stages. On stress induction, endogenous β-carotene was rapidly relocated from the photosynthetic pigment bed to the periphery of the chloroplast (Figure 6.1). After a number of hours, photosynthetic activity recovered with the cell re-establishing a maintenance mode, during which β-carotene accumulated together with high levels of metabolic activity.

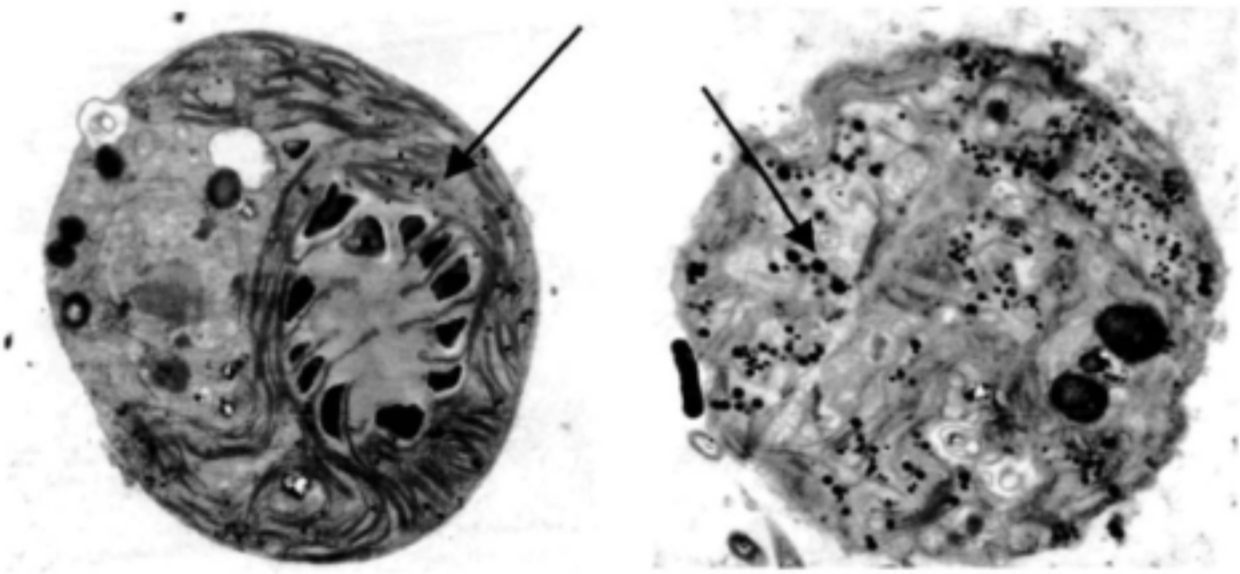


Figure 6.1. Electron micrograph of *Dunaliella salina* cells showing the accumulation of β-carotene globules (arrows) in cells produced in the averaged system (left) compared to the Dual Stage Process stress unit process (right).

Logie (1995) and Phillips L (1995) undertook studies in an attempt to further elucidate physiological components of the stress response process. They recorded the inhibition of carbon fixation, and oxygen evolution, immediately after stress induction, and also changes in cell volume associated with transient high abscisic acid levels measured 6-8 hours after the introduction of stress. This was found to be associated with carbon flux through the xanthophyll pigment cycle, and changes in intracellular pH in individual compartments within the cell. It was shown, in nuclear magnetic resonance (NMR) studies, that exposure to high light resulted in the rapid acidification of the chloroplast stroma, and in combination with chlorophyll fluorescence, that this stage is completed after about 4 hours. Homeostasis is then reestablished, and the cell becomes committed to the hyper-accumulation process. These studies led to the publication of a review of *Dunaliella salina* as a model system for studying the response of plant cells to stress (Cowan *et al*., 1992).

These studies also formed input components in the development of the stress stage of the DSP. Following cell growth, biomass is separated from the growth medium and transferred to a stress medium where the β-carotene accumulation stage is induced, and the hyper-accumulation stage is managed (Figure 6.2).

With optimisation of the components of stress physiology in *Dunaliella*, and using HRAP mass cultures of the organism, it was shown that saline wastewaters could be used for the commercial production of the high-value metabolite β-carotene, in addition to the recovery of protein, fatty acids and other cellular products. The scale-up evaluation of the DSP was undertaken in association with Sasol Co., with intermediate studies completed in Sasolburg. Using outdoor HRAP units, it was shown that the DSP consistently delivered around three times the β-carotene yield available from the best alternative growth averaging process. Scale-up studies included the evaluation of cell harvesting techniques, using membrane cross-flow filtration, flocculation and dissolved air flotation, and also β-carotene extraction processes including hot oil, supercritical CO_2, and solvent extraction operations. The DSP was then subjected to extensive and detailed evaluation in pilot-scale studies undertaken at a specially constructed pilot plant in Uppington, North Western Province. Economic evaluation and process design results for the DSP development study have been reported by Phillips T (1994).

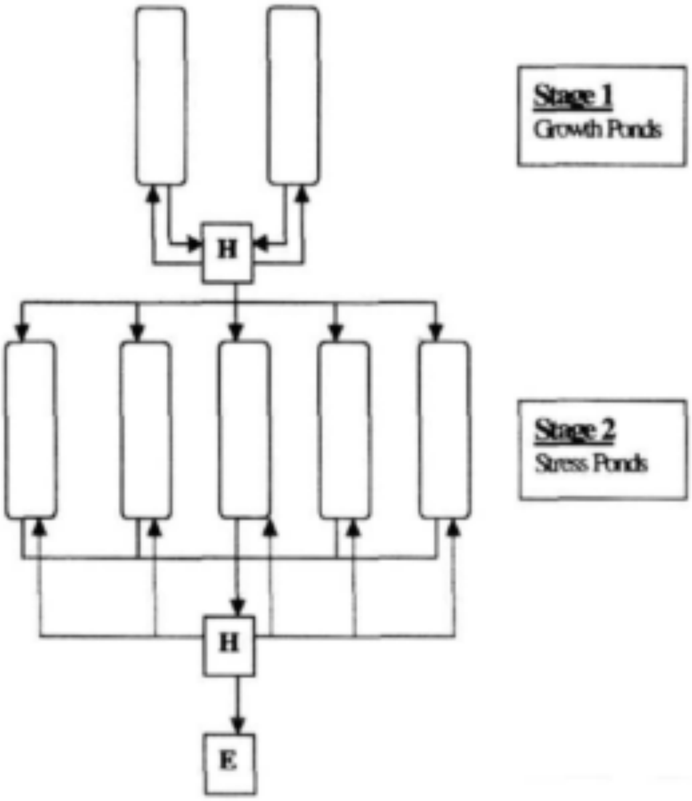


Figure 6.2. Schematic diagram of the Dual Stage Process for β-carotene production utilising D. salina cultures. Production of algal biomass is maximised under optimum growth conditions in Stage 1 growth ponds. This is followed by harvesting of biomass (H) and the return of growth medium to the growth ponds. The harvested biomass is then transferred to the Stage 2 stress ponds, where the stress induction process is initiated, and held there until appropriate concentrations of β-carotene have been produced. Biomass is once again harvested and passes to the β-carotene extraction stage (E) and the separated stress medium is returned to the Stage 2 ponds.

6.2.3 *Dunaliella*-HRAP Treating Solar Evaporites

At the time the above stress response studies were under investigation, an opportunity arose to evaluate the performance of the D-HRAP in the treatment of solar evaporite brines. Evaporation ponds used for the production of salt, soda ash and other evaporites are particularly susceptible to blooms of halophilic algae and bacteria, and this often results in high levels of contamination of the final product by organic compounds.

The initiation of the soda ash solar evaporite production facility in 1991, by Soda Ash Botswana (Pty) Ltd. at Sua Pan, in Botswana, had been followed shortly thereafter by the accumulation of high levels of organic materials contaminating the final product. Preliminary evaporation pond ecology studies had demonstrated the involvement of *Dunaliella* in this process, and that high levels of sulphide, phosphates and nitrates, in the influent brine pumped from wells in the Sua Pan, was probably driving the process. It was shown that high light intensity and elevated temperature stresses, in these hyper-saline carbonate brines, resulted in the extensive production of extracellular polymeric substances (EPS) by *Dunaliella*. Hitherto, the role of micro-algal organic contamination in solar evaporite production had been shown for sodium chloride production, where this form of contamination may have serious economic impacts on raw salt production in particular. Few practical measures are available for its treatment.

Masemola (MSc, 2000) has reported NMR studies which confirmed the role of *Dunaliella* exo-polysaccharide production as a component of the organic contamination of the product. Unique sugar combinations were identified in the exoploysaccharide produced by *Dunaliella* cultures, both in defined medium, and in pond brines, and also in the final soda ash produced.

The study also included the evaluation of a D-HRAP to be used to strip both nutrients and contaminating organics from the evaporation ponding process. Reducing nitrogen and phosphate levels was shown to provide an effective approach in manipulating microbial growth in the system. A pilot D-HRAP was constructed and operated on-site at Sua Pan, treating pond brines (Figure 6.3). It was shown that nutrient removal could be effectively handled in this operation and that the subsequent growth of *Dunaliella* in the brines treated in this way was substantially inhibited.

Figure 6.3. The *Dunaliella*-HRAP pilot plant treating saline carbonate brines at Botswana Ash Co., Sua Pan, Botswana.

While the pilot plant study has not yet led to the full-scale application of the process development, it was nevertheless shown that the D-HRAP might play an important role in the management of algal production in saline wastewater impoundments, especially where solar evaporites are to be produced, either as a product, or for the linear removal of contaminating salts from the water system.

6.3 CONCLUSIONS

Although the D-HRAP for the treatment of hyper-saline organic wastewaters was not subjected to detailed scale-up evaluation in pilot plant studies, in the way that the S-HRAP and the DSP β-carotene production process applications had been investigated, evidence from laboratory, and also from the pilot studies noted here, have provided a provisional indication for the viability of the process. The full-scale evaluation of a D-HRAP for the treatment of hyper-saline organic wastewaters remains to be undertaken. Nevertheless, these process studies in hyper-saline wastewater treatment did give rise to the development of the DSP, and the scale-up evaluation of the D-HRAP, as a nutrient stripping system in the production of solar evaporites. This system may find wider use in solar salt production.

In addition to the process development products derived in this initiative, which provide additional technology options in which saline wastes may be handled, these studies have also demonstrated a utility for saline wastewaters. It has been shown that impoundments of these waters need not necessarily be considered an environmental liability, but rather that a potential value is available in their treatment, providing 'integrated wastewater resource management' objectives, and sustainability with respect to the salinisation problem. It is also apparent that the hyper-saline HRAP may be considered as a pre-treatment option to remove organic compounds and contaminating metals from brine concentrates prior to their final disposal in saline wastewater impoundments.

7 THE BIOTECHNOLOGY OF SULPHATE-SALINE WASTEWATER TREATMENT: BIODESALINATION AND THE RHODES BioSURE PROCESS®

While sulphate-enriched wastewaters are generated in a number of industrial processes, including tanning, paper manufacture and metals processing, the main contributors to large-scale pollution from this source in South Africa are the gold and coal mining industries. Both biological and physico-chemical processes, set in train by mining operations, give rise to the oxidation of sulphur species, and the resultant generation of AMD. The Vaal River catchment system is one of the most affected, and receives large tonnages of mining-related salinity as both direct discharges, and in diffuse run-off flows.

Considerable effort has been expended in the treatment of directly pumped mine dewatering discharges, with volumes up to 135 $ML.day^{-1}$ treated by the high density sludge (HDS) process in the case of the Grootvlei Gold Mine alone. Earlier confidence that on mine closure water levels would rise to a subsurface steady level, and that the need for further treatment would then fall away, has now been largely discarded. Scott (1995) has shown that on closure Witwatersrand mines are likely to fill and than decant large volumes of highly polluting AMD, with some informal estimates putting this at around 500 $ML.day^{-1}$ for the combined East, Central and West Rand basins. Apart from contamination of groundwater resources, particularly in the dolomites, this water will require treatment before it reaches the public water system. While the time-scale over which care and treatment will be required is also uncertain, best estimates indicate an ongoing commitment lasting from many decades to several centuries (Younger *et al*., 1997). The long-term burden of this problem, and sustaining ongoing treatment over the time-frames involved, will almost certainly fall on the community, despite progressive mine closure legislation and comprehensive regulation governing the polluter-pays principle. South African coal mines face broadly similar problems.

The volume and time-frame of the AMD problem, and the need for a long-term and sustainable response has focussed interest in biological treatment approaches. These have concentrated on active and passive treatment systems, both of which rely on microbial activity related to the biological sulphur cycle, including bacterial sulphate reduction and the associated precipitation of metals as sulphide salts (Kuenen and Robertson, 1992; Johnson, 1995). Notwithstanding the reactor type, and the particular treatment approach used, widespread application of active biological AMD treatment has not yet been seen on any large scale. Singular factors constraining process development are bioreactor design, cost of bioreactor construction, and particularly the cost of the carbon and electron donor source for the biological sulphate reduction process. The sulphate reducing bacteria (SRB) are able to utilise only a limited range of small organic molecules.

Numerous SRB reactor design studies have been reported including trench reactors (Younger *et al*., 1997), anaerobic filters (De Walle *et al*., 1979; Chian and De Walle 1983), mixed reactors (Maree and Hill, 1989), packed bed anaerobic bioreactors (Riviera, 1983; Maree *et al*., 1987) fluidised bed systems (Umita *et al*., 1988; Van Houten *et al*., 1994), sequencing batch reactors (Herrera *et al*., 1991), the upflow anaerobic sludge bed

(Buisman *et al*., 1989; Barnes *et al*., 1991) and the baffle reactor (Grobicki and Stuckey, 1992). The evaluation, in the active AMD treatment application, of a range of carbon sources has also been reported (Rose *et al*., 1998), including sewage sludge (Butlin *et al*., 1956; Pipes, 1961; Burgess and Wood ,1961; Conradie and Grutz, 1973), animal waste slurries (Ueki *et al*., 1988); straw, hay and lucerne (Bechard *et al*., 1993); lactate and cheese whey (Olezkiewicz and Hilton, 1986; Herrera *et al*., 1991) molasses (Maree and Hill, 1989), ethanol and methanol (Postgate, 1984; Szwezyk and Pfennig, 1987) and producer gas (Du Preez and Maree, 1994; Van Houten *et al*., 1994). In passive systems wetland plantings of Sphagnum sp., Typha latifolia and Phragmites australis have been used, and may provide a carbon source to these systems of up to 40 $ton.ha^{-1}.year^{-1}$ (Wieder and Bennemann,1993).

Despite the wide range of bioreactor and electron donor options examined, the effective engineering of active biological AMD treatment processes has concentrated largely to date on relatively high-cost bioreactor systems, and carbon sources such as ethanol (Johnson, 2000).

The studies reported here were motivated by the requirements for technology which would be sustainable over the long periods of time for which it is anticipated treatment will be required, and also for the low-cost treatment of high volume flows. These requirements focussed research activity on bioprocess developments using relatively simple bioreactor designs and complex organic compounds derived from waste streams as electron donor sources, and the integration of AMD treatment with other waste treatment objectives. The co-disposal of organic wastes with AMD treatment would enable the development of an 'integrated wastewater resource management' approach to the problem, including sustainability of treatment operations over the long time-frames involved. Apart from the cost advantages accrued to waste treatment, and the beneficiation of organic wastes as a bioprocess feedstock, the recovery of the treated water as a resource for the wider community provides a potentially important value-added function to the combined operation (Rose *et al*., 1998). In the case of wastewater co-disposal the 'integrated wastewater resource management' objective falls within the domain of the public utility operator, where treatment of mine water flows may be more effectively managed over the very long periods of time anticipated.

The surprising observation in the tannery IAPS of an efficient solubilisation and removal of organic particulates, and high rates of sulphate reduction in their anaerobic compartments, led to a series of follow-up studies on the phenomenon of enhanced hydrolysis apparently occurring in these systems. This R&D activity, which demonstrated the potential available in linking biological sulphur cycle process development and the hydrolysis of particulate organic carbon, commenced within Project K5/495. It was followed up in four related WRC projects and resulted in the development of a number of bioprocess initiatives which are summarised here.

7.1 PONDING SYSTEMS AND THE ASPAM PROCESS

The observations of high rates of sulphate reduction, utilising complex organic substrates present in tannery effluents as carbon and electron donor source, provided an indication that ponding systems might themselves be used as bioreactors for the large-scale biological treatment of AMD, and with the anaerobic compartments in these systems serving as effective bioreactors for the sulphate reduction reactions.

While WSP technology has been developed over the past 40 years for a wide range of wastewater treatment applications (Mara and Marecos Do Monte 1987; Mara *et al*., 1996) little attention, if any, has focussed on the use of these systems for AMD remediation. Principal advantages of using the WSP as a basic design concept around which to develop AMD treatment processes are that:

- the linkage between the treatment of large volumes of wastewaters and mass algal production has been firmly established as a mature and widely utilised operational technology (Mara *et al*., 1996);
- the earthwork pond provides a reactor at least an order of magnitude less costly to construct than steel-reinforced vessels (Oswald 1995);
- renewable algal biomass as a potential carbon source for sulphate reduction may be reliably produced in large amounts (up to 50 $tons.ha^{-1}.yr^{-1}$) in separately optimised high rate systems (Oswald 1988b);
- anaerobic ponds may support high levels of SRB activity (Pescod 1996);
- the use of complex organic carbon as an electron donor for sulphate reduction has been demonstrated (Rose *et al*., 1998; Boshoff, 1998; Whittington-Jones, 2000);
- the precipitation of heavy metals in sulphate reducing WSP, with concentrations lowered to residuals in the ppb range, has been demonstrated for the system (Rose *et al*., 1998; Dunn, 1998; van Hille *et al*., 1999).

Project K5/656: 'Appropriate low-cost treatment of sewage reticulated in saline water using the algal high rate oxidation ponding system', commenced in 1995 and was to undertake a preliminary evaluation of the co-disposal of sewage sludge and saline wastewaters. Results acquired here showed the use of tannery effluent and sewage sludges as potentially effective electron donors, and carbon sources, in sulphate-salinity reduction applications in particular. This development was followed up in 1997 in Project K5/869: 'Biological sulphate desalination and heavy metal precipitation in industrial and mining effluents using the IAPS', which ran concurrently with Project K5/656, and resulted in the conceptual development of the ASPAM Process.

Figure 7.1 illustrates the fully configured ASPAM process. In its simplest form, it involves the settling of metal sulphide sludges in the anaerobic compartment of a facultative pond which is fed some source of organic waste material together with AMD in a co-disposal operation. In addition to providing algal biomass as an independent carbon source, and the final polishing of metals from the waste stream, the HRAP may also be used to provide control of sulphide release, with the recycle of an oxygen-rich cap to the surface of the facultative pond. Sulphides may be fed to the influent mine water, in solution or in gaseous form, and together with alkalinity from the HRAP, effect the precipitation of contaminants as metal sulphides, which can then be removed from the system.

The conceptual design for the ASPAM process was demonstrated in laboratory investigations, and in a number of pilot-scale evaluation studies of the individual unit operations comprising the integrated process, undertaken in WRC Project K5/869. A follow-up project to undertake the construction of a pilot plant, and comprehensive piloting of the full integrated process, was not implemented due to the shift of focus to the Grootvlei Mine dewatering problem described below.

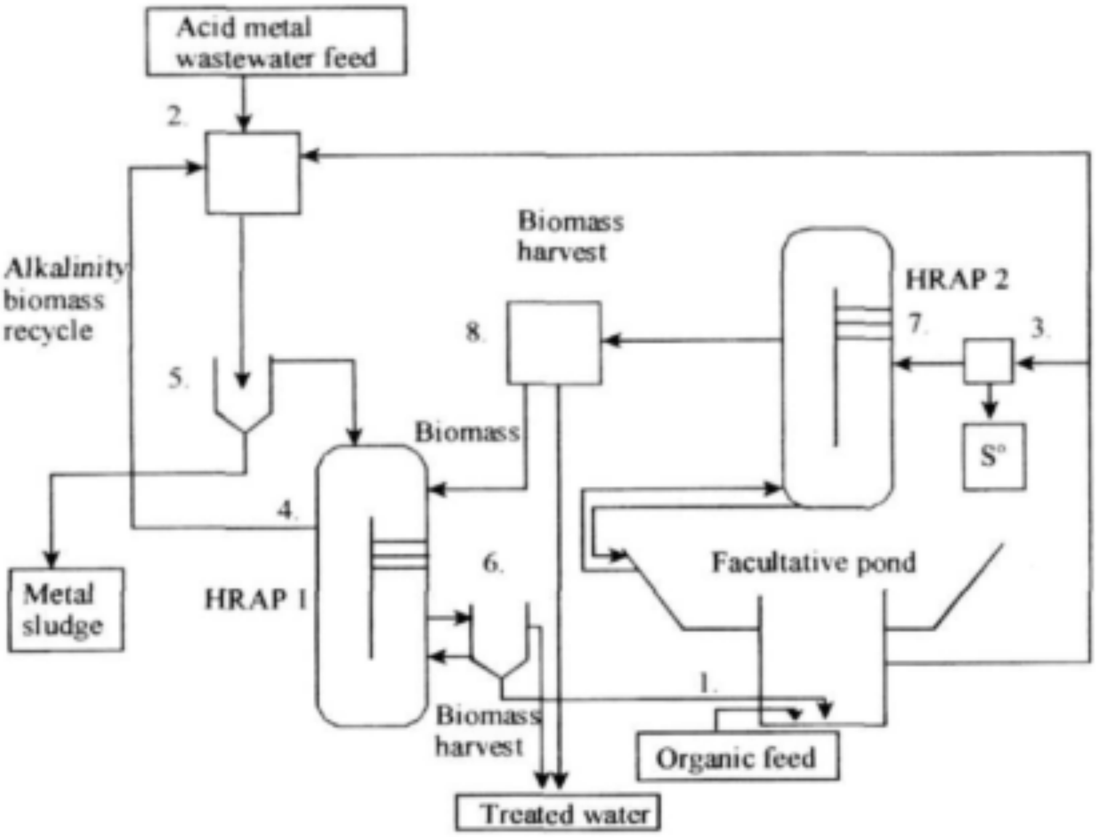


Figure 7.1. Flow diagram of the individual unit operations of the Integrated Algal Sulphate Reducing Ponding Process for Acid Metal Wastewater Treatment (ASPAM). Organic feed enters at 1= Facultative pond with anaerobic upflow digester compartment; Feed water enters at 2 = Inlet and metal precipitation unit; Sulphide is recycled to metal precipitation unit from 3 = sulphide recycle and sulphur recovery unit; Alkalinity and algal biomass generated in High Rate Algal Pond (HRAP)1 recirculated via 4; 5 = Metal sludge settler; 6 = Algal biomass settler; 7 = High Rate Algal Pond (HRAP)2 for capping the Facultative Pond and seeding HRAP 1 with fresh biomass; 8 = Algal biomass harvester.

7.2 GROOTVLEI AND THE RHODES BioSURE PROCESS®

Where the tannery IAPS study had shown that ponding systems might indeed be feasibly considered for the large-scale treatment of sulphate wastewaters, and that complex carbon sources might be efficiently mobilised in ponds for sulphate reduction activity in these systems, it was also evident that the hydrolysis reactions might equally be managed and optimised as free-standing unit operations in customised bioreactors. It was also evident that the design of these might be configured taking into account the particulate solubilisation mechanisms observed both in natural environments and in wastewater ponding systems studied. Follow-up studies based on these assumptions resulted in the development of the WRC patented Rhodes BioSURE Process®.

Scale-up evaluation studies for the use of sewage and tannery wastewaters as potential electron donor sources for sulphate reduction, had been planned to be undertaken at Seton Leathers Co. and the East Rand Water Care Company's (Erwat) Bickley Sewage Works in Nigel, South Africa. This was also to have included evaluation of the ASPAM Process. However, at this time the Grootvlei environmental-incident intervened. Closure of gold mines on the East Rand over a period of years had shifted the burden of dewatering the East Rand Basin to Grootvlei Mine alone. The increased pumping and dewatering of the Grootvlei Gold Mine into the Blesbokspruit, and the resulting pollution impacts developed into a political issue of potentially international significance. Heavy metal and sulphate-saline pollution from the mine dewatering exercise threatened the Marievale and Daggafontein Bird Sanctuaries – Wetlands of International Significance under the Ramsar Convention, to which South Africa is signatory. Following a pump shutdown order by the Ministry of Water Affairs and Forestry, in 1996, a technology evaluation exercise was agreed as a prerequisite for the resumption of pumping, and which would undertake the comparison of technology options available to deal with the salinity and mine dewatering problem. Of 14 technology bids received 4 proceeded to on-site evaluation.

The WRC and Rhodes EBG were requested to incorporate the scale-up studies, then due to be undertaken in Nigel, into the nearby Grootvlei technology assessment exercise. A falling sludge bed reactor concept in which the hydrolysis reaction could be optimised, and based on an understanding of the performance of the tannery pond anaerobic compartments, was under evaluation at the time as a basic bioreactor design. This pilot plant was duly constructed during 1997, and located at Grootvlei Mine early in 1998 (Figure 7.2). Given the extreme time constraints imposed by these developments, and the need to respond immediately, the initial phases of the programme were covered in the tail end of projects K5/656 and K5/869. At the same time, and due to the novelty of the exercise, it became apparent that fundamental issues emerging from the development of the process needed to be addressed concurrently with the piloting exercise, in order to ensure that both the theoretical and practical requirements of the project were met.

Figure 7.2. Headgear at the No.4 shaft Grootvlei Mine with the Rhodes BioSURE Process® pilot plant in the foreground. Reactors were constructed in Grahamstown, and then transferred to site.

WRC 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', commenced as a three-year study in 1998, and resulted in the establishment of collaborative projects with Profs Geoff Hansford and Dick Loewenthal, and Dr Alison Lewis of the University of Cape Town Departments of Chemical and Civil Engineering. Pilot studies and process developments were followed in WRC 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'.

Following completion of the Grootvlei pilot study in 1999, an experimental BioSURE® pilot plant was constructed at the Rhodes University Environmental Biotechnology Experimental Field Station, located at the Grahamstown Disposal Works to undertake follow-up studies. The Experimental Field Station was officially opened by the Executive Director of the Water Research Commission, Mr P. Odendaal, in January 2000 (see Appendix 3.3).

Based on the insights acquired in the hydrolysis of sewage sludges in sulphate reducing environments, and following the above developments, it was shown that the BioSURE Process®, in addition to AMD treatment, also offered the associated potential to be used in the disposal of sewage sludges, where an external sulphate source could be provided. This was followed up in Project K5/1169: 'Intermediate scale-up evaluation of the Rhodes process for hydrolysis and solubilisation of sewage sludges in a sulphate reducing bacterial system', a collaborative programme with Erwat.

The interrelated and iterative R&D exercise which resulted in the development of the Rhodes BioSURE Process® linking sulphate-saline mine wastewaters and PSS disposal, is described in its separate phases, and the principle findings are noted below.

7.3 SULPHATE REDUCTION USING COMPLEX ORGANIC CARBON SOURCES

As noted earlier, most high-rate sulphate reduction bioprocess developments have relied on the use of simple molecules as electron donors for SRB activity. The potential hydrolysis of complex carbon substrates to provide a feedstock for the SRB became the focus of the following studies.

7.3.1 Tannery Wastes

Studies in the microbial ecology of the tannery effluent WSP in Wellington, noted above, had shown a surprisingly effective degradation of particulate organic solids in association with a complete biological sulphur cycle, operating in the pond water column.

These observations were subjected to more systematic investigation in a series of studies undertaken in 1 m^3 bioreactors, using untreated tannery effluent as the feed source, and set up at the Seton Tannery in Nigel. The performance of two sulphate reducing reactor configurations was compared (Figure 7.3), including the simulation of the bottom-fed pond in an upflow reactor (Reactor A) and a stirred tank reactor incorporating a solids return loop (Reactor B). Results of these studies have been reported by Boshoff (1998) and Rose *et al*., (1998).

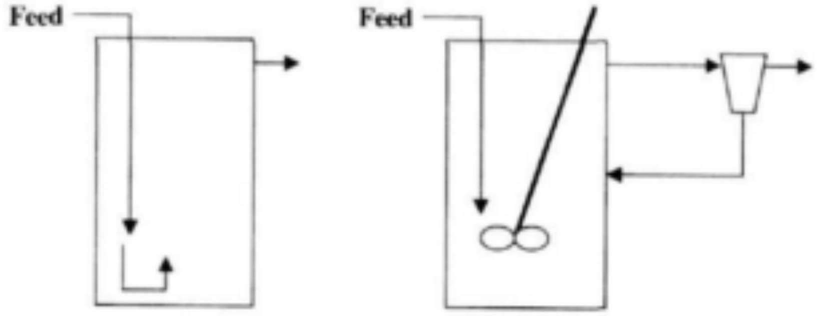


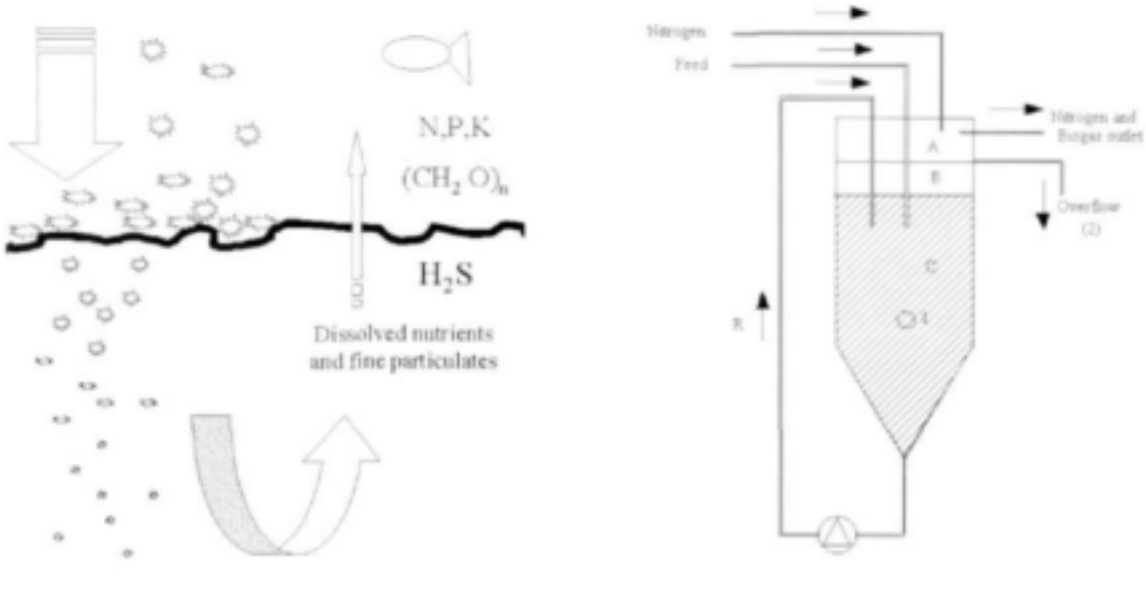
Figure 7.3. Comparison of two sulphate reducing reactor configurations. The bottom-fed upflow reactor (A) and the stirred tank reactor (B) with sludge recycle.

Sulphate reduction was found to be nearly twice as efficient in reactor A, with average $COD:SO_4$ conversion ratios of 1.2:1 compared to 2.3:1 in Reactor B, over a 30 day steady state performance period. As expected from the ponding studies settleable solids did not accumulate measurably in Reactor A. While a low solids accumulation was anticipated for Reactor B, the settleable solids discharged in the effluent of Reactor B was around 30 $mL.L^{-1}$ compared to 1 to 3 $mL.L^{-1}$ in Reactor A. These results indicated not only more effective sulphate reduction in Reactor A, but possibly also that sulphide and alkalinity gradients established within the system may play an important role in the particulate degradation function by which complex molecules are made available to SRB activity.

7.3.2 Primary Sewage Sludge Solids

Investigations similar to those reported for tannery effluent were undertaken using PSS as the electron donor for sulphate reduction. Once again $1m^3$ bioreactor studies were undertaken and the results showed the effective degradation of particulate organic matter to be associated with efficient sulphate reduction/organic carbon utilisation ratios. These results have been reported by Molepane (MSc, 1999).

The observations of effective degradation of organic carbon occurring within these reactor systems appeared to indicate a particular role for sulphate reduction in the solubilisation processes involved, and these were apparently of importance in the processes by which complex carbon substrates were made available to SRB activity. In natural environments such as sulphate reducing sediments, and in the ponding system studied, the size of particulate matter may be observed to decrease against increasing sulphide and alkalinity concentration gradients (Figure 7.4a). Where an upwelling incident occurs, nutrients, partly degraded small organic molecules and residual slowly degrading organic particulate matter pass back up into the water column. Solubilised components support ongoing nutrient cycles, and the remaining undegraded settleable particulates return to the sediment for another round of solubilisation activity, yielding ultimately the full hydrolysis of the degradeable organic fraction.



A B

Figure 7.4. The breakdown of particulate organic matter in natural sulphidogenic settlement and sedimenting processes (A) was simulated in a 1L prototype study (B) of the Recycling Sludge Bed Reactor (RSBR). The degrading sludge is returned via line R to blend with the incoming feed.

Given the central importance of the solubilisation and hydrolysis reactions as the initial steps in which complex organic carbon structures are made available to biological processes, the apparent advantages of the recycling sedimentation process was subjected to more detailed investigation in the Recycling Sludge Bed Reactor (RSBR) study described below.

The prototype RSBR was constructed as a 2L bench-scale single stage reactor (SSR) unit (Figure 7.4b), and sulphate-enriched PSS was used as the feed (COD = 4000 mg.L^{-1}; SO_4^{2-} = 2000 mg.L^{-1}). In this unit solids settling in the reactor are drawn down into the falling sludge bed where sulphate reduction commences and the build-up of sulphide and alkalinity is observed. The sludge is drawn down the bed and is then recycled to blend with the influent flow simulating the upwelling events observed in the pond systems. Floc growth entraps new particulate matter which, together with residual and as yet undegraded settleable solids, returns to a further round of sludge recycling. Solubilised solids pass out of the reactor in the liquid stream. The subsequent use of the soluble organic fraction as electron donor for sulphate reduction was investigated in a multi-stage RSBR unit (Figure 7.5). The results of this study have been reported by Whittington-Jones (PhD, 2000).

The scale-up development of the RSBR formed the basis of the BioSURE® pilot plant constructed at Grootvlei Gold Mine and the results of these studies have been reported by Whittington-Jones (2000), Corbett (MSc, 2001) and Molwantwa (MSc, 2002).

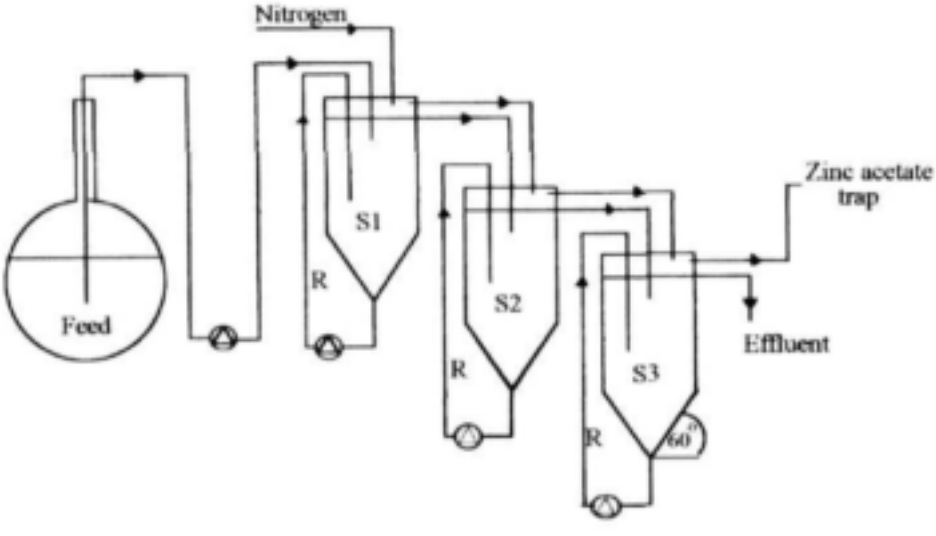


Figure 7.5. The multi-stage Recycling Sludge Bed Reactor used to investigate the solubilisation of primary sewage sludge and its utilisation as an electron donor source in sulphate reduction activity.

7.3.3 Solubilisation of Particulate Organic Carbon

Hydrolysis is generally regarded as the rate limiting step in anaerobic pathways responsible for the degradation of complex organic carbon structures, in both natural and bioprocess environments (Eliosov and Argaman, 1995; El-Fadel *et al.*, 1996; Vavilin *et al.*, 1996; Penaud *et al.*, 1997). The rate at which hydrolysis proceeds is described by first order kinetics and may be strongly influenced by both environmental and operational parameters, including the concentration of particulate substrate and soluble products (Eastman and Ferguson, 1981; Shimizu *et al.*, 1993). Particle size, in particular, has been shown to have a profound impact on the rate of the anaerobic digestion of complex substrates (Choi *et al.*, 1997; Madhukara *et al.*, 1997; Müller *et al.*, 1998). Wentzel *et al.*, (1995) demonstrated a size related criterion of 0.1 mm separating rapidly-biodegradeable from slowly-biodegradeable and refractory COD.

Sewage sludge has received attention as a model system for studies in the degradation of particulate organic matter (Vavilin *et al.*, 1996), due in part to the ubiquitous nature of the disposal problem, but also in the potential use of the solubilised product as an electron donor source in a range of bioprocess applications. These include biological nutrient removal processes in wastewater treatment (Brinch *et al.*, 1994; Skalsky and Daigger, 1995; Hatziconstantinou *et al.*, 1996; Banister and Pretorius, 1998), biological sulphate reduction in AMD wastewater treatment (Molepane, 1999 and Whittington-Jones, 2000), and other potential bioprocess applications related to waste disposal operations including, more recently, an interest in the utilisation of organic wastes in sustainable 'integrated wastewater resource management' strategies.

However, solubilisation rates for PSS are slow in conventional anaerobic digestion systems (Pipyn and Verstraete, 1979), with maximum soluble product formation reported between 8 and 20 days, and at yields of 5-10% in the mesophyllic temperature ranges (Canziani *et al.*, 1996; Hatziconstantinou *et al.*, 1996; Banister and Pretorius, 1998; Elefsiniotis and Oldham, 1994; Shimizu *et al.*, 1993). Effective separation and recovery of the solubilised product from the residual sludge imposes further constraints on bioprocess applications (Banister and Pretorius, 1998).

Pipes (1961) had suggested that stabilization of PSS under sulphate reducing conditions might offer particular advantages for disposal of sewage sludges, and Butlin *et al.*, (1956), and Burgess and Wood (1961) had noted potential for sulphide and sulphur production from sulphate-enriched sewage. While these early suggestions of sulphate assisted PSS digestion have remained largely unexplored, more recent studies have shown that the rate and extent of lignocellulose solubilisation, an abundant compound in primary sludge (Elefsiniotis and Oldham, 1994), was enhanced in the presence of sulphur compounds in both sewage and landfill environments (Khan and Trottier, 1978; Kim *et al.*, 1997; Pareek *et al.*, 1998).

The simulation of the reciprocating sedimentation and upwelling events observed in the pond study (Figure 7.4a), provided an experimental system with which to test a descriptive model of enhanced solubilisation of PSS under sulphidogenic conditions. It suggests that the mechanisms observed may have more general application in understanding degradation of particulate organic carbon structures in natural sulphate reducing environments. It was proposed that the solubilisation of PSS was enhanced under sulphate reducing conditions as a result of enhanced hydrolysis of the macromolecular protein and carbohydrate constituents. Furthermore, it was suspected that this would result in a reduction in the mean size of sludge flocs, and thus also contribute to the enhanced solubilisation of the PSS. Reactor configuration seemed to be important in the concentration of reactants achieved at the bottom of the settling cycle.

Jain *et al.*, (1992) modelled the anaerobic digestion of complex particulate substrates, and showed that two factors which had the greatest impact on the rate-limiting hydrolysis step were the concentration of the hydrolytic enzymes, and the contact between these enzymes and their substrates. Vavilin *et al.*, (1996) proposed that the hydrolysis rate constant was a function of the ratio between the characteristic sizes of the hydrolytic bacteria and the substrate particles, and was thus dependent on the colonisation of the particle surface by hydrolytic bacteria. The efficiency of particulate solubilisation may, therefore, depend on more than just reaction mechanism and reactor configuration. Operational factors which increase the enzyme concentration, or reduce mass transfer limitations, should result in an increase in the rate of hydrolysis.

7.3.4 Particle Size Reduction

A comparison of the +sulphate and -sulphate fed bench-scale RSBR units showed enhanced breakdown of PSS particulates within the bed under sulphate reducing conditions (Figure 7.6), and that this was associated with the consumption of COD in the sulphate reduction reaction. The multi-stage reactor system, separated into primarily particle solubilisation in reactor 1, and sulphate reducing unit processes in reactors 2 and 3, showed a nearly three-fold improvement in COD utilisation through sulphate reduction, compared to the SSR .

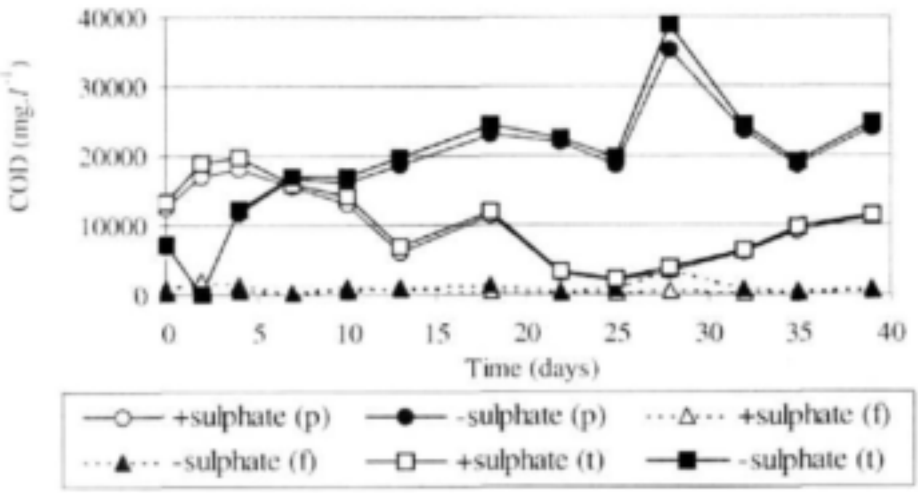


Figure 7.6. The concentration of COD within the bed of the first of the multiple-stage bench-scale reactors fed primary sewage sludge. The total (t), particulate (p) and filtered (f) COD are compared for the sulphate reducing (+ sulphate) and non-sulphate reducing (- sulphate) bioreactor systems.

Washout of particulate matter (CODp) from the +sulphate reactors was related to the fracturing of the PSS floc under sulphate reducing conditions, and giving rise to the production of progressively smaller sized particulates. Floc area measurement (Figure 7.7) showed that while the floc sizes of PSS may be variable over quite a large range, size reduction is significant (Kruskal-Wallis Analysis, $P<0.001$; $df = 17$), and is quite rapid in the +sulphate system, commencing already in the feed blend tank.

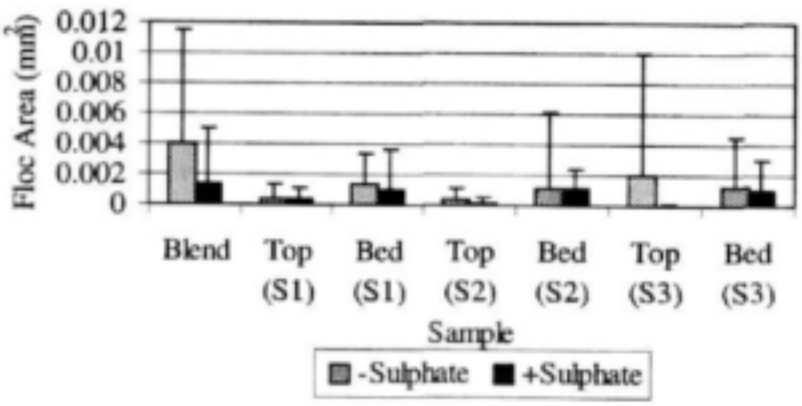


Figure 7.7. Mean area of sludge flocs within the feed and three stages of the sulphidogenic (+ sulphate) and non-sulphidogenic (- sulphate) multiple-stage bench-scale bioreactors. Bars indicate standard deviations and the primary sludge feed values for both systems were equivalent to the - sulphate blend value.

The recirculation of the settled sludge in the reactor bed of the +sulphate system resulted in the inclusion of dense particulate matter into the substance of the incoming floc material (Figure 7.8). While the nature of this inclusion was not identified, it appeared to include a metal sulphide precipitate possibly associated with SRB activity.

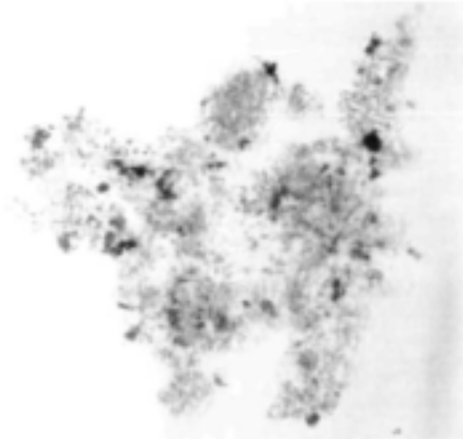


Figure 7.8. Floc morphology showing the dense particulate matter embedded within extracellular polymeric materials (light microscope 40x magnification).

Studies on the cleavage of the PSS flocs into progressively smaller-sized particulates indicated that the solubilisation was related to the hydrolysis of carbohydrate and protein fractions present in the PSS flocs. An increase in total soluble phenol observed during solubilisation reactions (Figure 7.9) indicated that the cleavage of lignocellulose may also be involved, and that these hydrolysis reactions were enhanced under sulphate reducing conditions. It was also observed that enzyme activity accumulated in the sludge bed compared to substantially lower levels in the incoming stream.

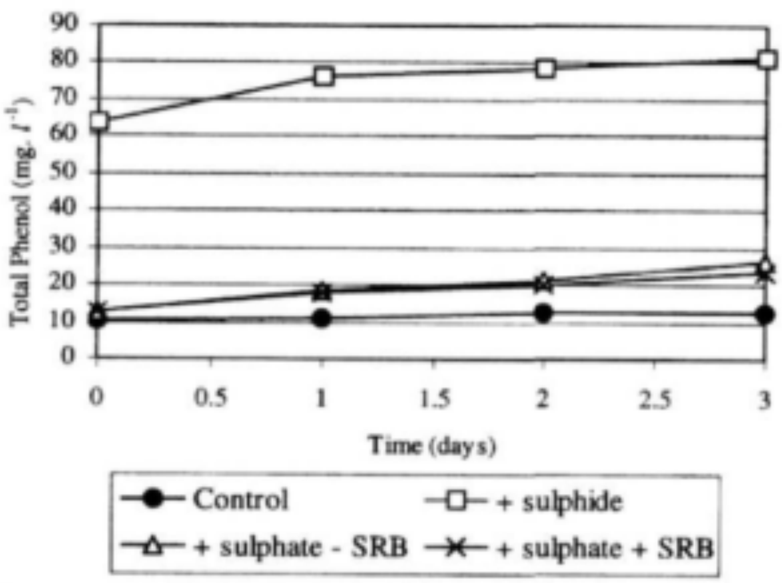


Figure 7.9. The effect of sulphide and sulphate reduction on the concentration of total soluble phenol in primary sewage sludge when digested anaerobically. The +sulphide value represents an elevation from 10.2 to 63.5 mg.L^{-1} phenol within a period of a few minutes.

7.3.5 Interpretation of Results

The mean size of flocs within a digester is dependent on the relative rates of flocculation and floc fracture. Constant floc growth is offset by enzymatic (Nielsen *et al.*, 1996) and shear-induced (Spicer and Pratsinis, 1996) floc fracture. The smaller mean floc size in the sulphidogenic laboratory-scale reactors indicated that floc fracture was accelerated under those conditions. The mechanism of enhanced floc fracture in the RSBR is poorly understood, but is likely to involve enhanced solubilisation of carbohydrates and proteins, in the presence of biological sulphate reduction. Little is known about the composition and formation of flocs in non-granulating anaerobic digesters. If it is assumed that the composition and structure of these flocs is similar to those in non-bulking activated sludge systems, then it is likely that a significant proportion of the flocs would be proteins and carbohydrates, held together by non-covalent bonds (Forster, 1982; Eriksson and Alm, 1991; Bruus *et al*., 1992; Urbain *et al*., 1993). The increased rate of floc fracture is most likely due to a loss of integrity of the floc due to enhanced hydrolysis of important structural components such as lignin, cellulose and proteins. Cinq-Mars and Howell (1977) provided further evidence for the importance of cellulose in maintaining the integrity of flocs in PSS. When they treated PSS with fungal cellulase, the gel-like characteristic of the raw sludge changed to that of a slurry of fine particles in less than 2 hours.

The incorporation of recycled particulates into the incoming flocs appears to involve their envelopment in non-particulate EPS. Li and Ganczarczyk (1990) suggested that the significant quantity of EPS in activated sludge flocs provided diffusional resistance to the movement of substrates and products to and from the flocs. Likewise, EPS and other macromolecular components of the flocs in anaerobic digesters may offer steric resistance to the passage of bacteria and hydrolytic enzymes. Although bacteria would also be incorporated into the growing flocs, the major part of degradation of floc components is likely to be from the outer surface where the concentration of bacteria will be high. As such, the macromolecules within the floc will be protected from enzymatic degradation. As the flocs disintegrate, macromolecules that were previously protected from enzyme attack are exposed, and may be degraded by hydrolytic enzymes. By increasing the frequency of floc cleavage, it is possible to facilitate hydrolysis by increasing the contact between enzyme and substrate. Furthermore, deflocculation will allow hydrolytic bacteria and their associated enzymes to penetrate into the floc matrix, where hydrolysis of previously unexposed macromolecules will take place. The rate at which freshly exposed particulate organics are degraded is related to the size of the particles, with small particles degraded more rapidly than larger ones (Torrijos *et al*., 1993; Wentzel *et al*., 1995; Vavilin *et al*., 1996).

As hydrolytic bacteria and hydrolytic enzymes are closely associated with the floc matrix, rather than in the supernatant liquid (Boczar *et al*., 1992; Frølund *et al*., 1995; Confer and Logan, 1998; Goel *et al*., 1998), they will tend to be concentrated with the settling particulate fraction. Accumulation of enzymes within the sludge bed of the RSBR, and the demonstration of particulate capture and encapsulation by incoming raw floc emphasised the importance of reactor design in the retention of both biomass and the bound hydrolytic enzymes. Figure 7.10 summarises a proposed mechanism for the enhanced solubilisation of particulate organic matter under sulphate reducing conditions.The results of this investigation indicate that the process of enhanced solubilisation relies on a reduction of floc stability in the presence of sulphide, and as a result of an increased rate of hydrolysis of lignocellulose, carbohydrates and proteins. Floc fracture and mixing are essential, and results in exposure of previously inaccessible macromolecules to cleavage by hydrolytic enzymes. The configuration and operation of the reactor appears to be critical to the optimum performance of the process due to mass transfer events occurring in the falling sludge bed, i.e. retention of biomass and enzymes, increased contact between particle bound enzymes and substrates, removal of soluble products and the maintenance of active sulphate reduction in close proximity to the hydrolytic reactions.

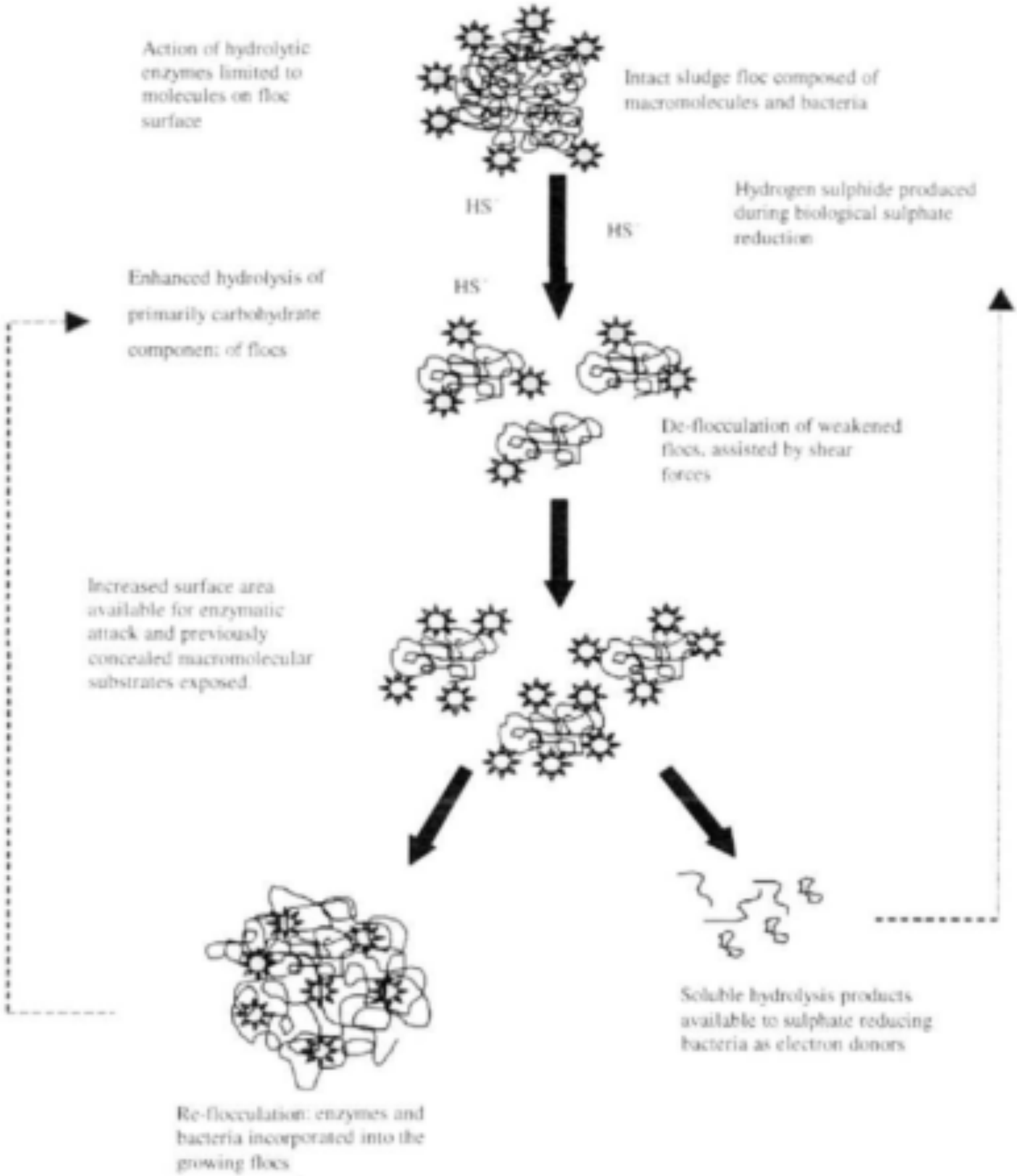


Figure 7.10. Flow diagram summarising the factors involved in the process of enhanced hydrolysis of primary sewage sludge under sulphate reducing conditions.

The operation of the RSBR may provide an account of particulate solubilisation with more general application in understanding the degradation and recycling of organic matter in sulphate reducing environments. These principles in the performance of the RSBR were applied in the scale-up development of the Rhodes BioSURE Process® pilot plant study at Grootvlei Mine.

7.4 THE RHODES BioSURE PROCESS®: 1 – THE BIODESALINATION OF MINE DRAINAGE WASTEWATERS

The studies described above had shown that the availability to biological sulphate reduction of complex organic carbon structures as electron donors, was dependent not only on the relevant hydrolysis reactions, but also on the configuration of the reaction environment. With reactor conceptualisation partly informed by the simulation of natural sedimenting environments, the RSBR was found to offer advantages in the optimisation of the solubilisation process. It was also found that the partial separation of carbon solubilisation and sulphate reduction reactions, in sequential unit operations, may offer opportunities for the more effective optimisation of the overall sulphate reduction process. Although a component of the influent COD and sulphate are consumed in the establishment of the enhanced hydrolysis environment, the solubilised product may be made available in a suitable form as a feedstock to an optimised downstream sulphate reduction unit operation.

While studies on the scale-up of the RSBR were undertaken, from the 2L bench-scale unit (Figures 7.4 and 7.5) to 10L and $1m^3$ prototype units located at the Environmental Biotechnology Experimental Field Station in Grahamstown, the application of the process in the removal of heavy metal contaminants from industrial effluents and AMD was also investigated. Results reported by Rose *et al.*, (1998) had demonstrated the metal removal efficiencies of both tannery and algal biomass-fed sulphate reduction systems.

7.4.1 BioSURE® at Grootvlei

The various research outputs described above led to the initial conceptualisation of what was to become known as the Rhodes 'BioSURE' Process applied to the treatment of AMD. Given the volume of the treatment requirement at Grootvlei Mine it was decided to concentrate on the use of sewage sludge as the most freely available carbon source. In the process design (Figure 7.11 and 7.12), the RSBR was incorporated as the first stage (Reactor 1) in a dual stage sulphate reduction operation.

Although some sulphate and COD would be consumed in the RSBR, its primary role would be the enhanced hydrolysis of the PSS as a carbon electron donor source. The solubilised product would pass to a second stage (Reactor 2) where the sulphate reduction reaction would be optimised. While a range of reactor designs could be used here, a Baffle Reactor was used in this application. A component of the alkalised and sulphide-enriched Reactor 2 effluent would pass to an AMD pre-treatment operation where neutralisation and heavy metal precipitation would be effected. Where a full biodesalination is to be optimised the reduced sulphate may be finally removed as S^0 in a sulphide oxidation step. Studies in the development of a Sulphide Oxidising Bioreactor (SOBR) are described below. A HRAP was used to effect polishing and disinfection of the final treated water. The process flow diagram for the BioSURE® plant at Grootvlei is shown in Figure 7.12.

Following construction of the BioSURE® pilot plant in Grahamstown in late 1997, it was reassembled at No. 3 Shaft at Grootvlei Gold Mine in January 1998. After a period of stabilisation, during which a viable bioreactor sludge bed was established, the plant was operated over a period of 18 months. The pilot study took the form of both a process development and technology evaluation exercise. Sewage sludge was supplied and delivered to site at the mine by Erwat who also, together with the WRC, sponsored a substantial component of this study.

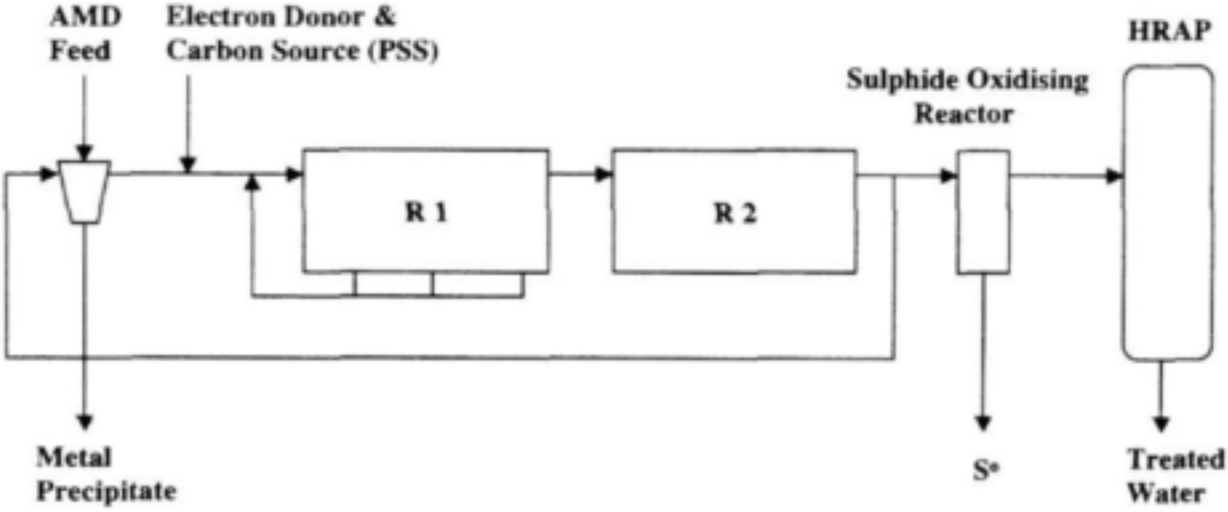


Figure 7.11. Process flow diagram of the Rhodes BioSURE Process® applied to the treatment of acid mine drainage wastewater (AMD). R1 = Recycling Sludge Bed Reactor; R2 = Baffle Reactor; HRAP = High Rate Algal Pond; PSS = primary sewage sludge. A side stream of sulphidic wastewater is blended with incoming minewater to precipitate contaminating heavy metals. The sewage sludge carbon source is added to the metal-free stream which passes to the RSBR where hydrolysis of particulates and some sulphate reduction occurs. The dissolved organic stream passes to a baffle reactor where it is used as the feedstock in the final sulphate reduction step. Sulphide oxidation may be effected by sulphide oxidation and removal of S^0.The treated water is then discharged via the HRAP polishing stage.

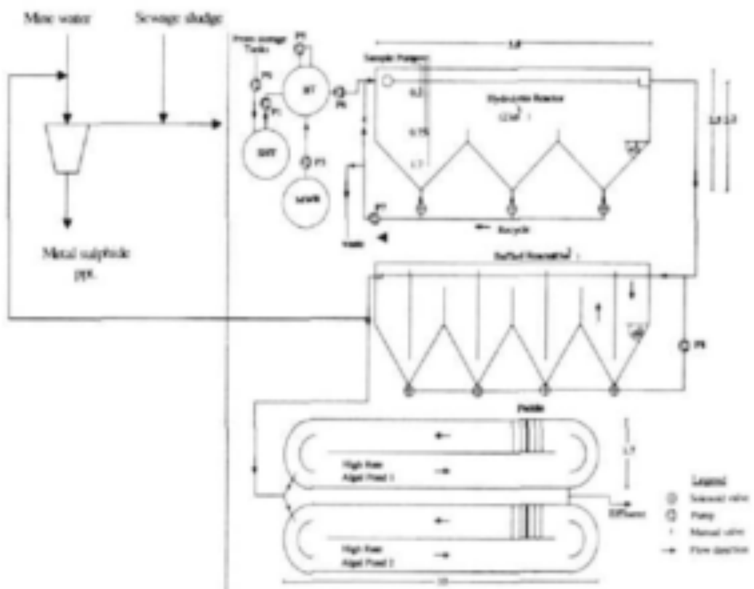


Figure 7.12. Process flow diagram of the Rhodes BioSURE® Pilot plant constructed at Grootvlei Gold Mine.

The sulphate reduction and COD consumption for steady state operating conditions across the process are summarised in Figure 7.13. These values were 70% and 71% respectively at an HRT across the system of 2 days. This increased to 77% and 78% respectively where the HRT in Reactor 2 was increased to 4 days. Performance data are summarised in Table 7.1.

In the Grootvlei pilot plant the major fraction of sulphide produced was discharged together with the reactor headspace gas. In a complete system this would need to be recovered as S^0 in a SOBR unit operation. This is the subject of a current WRC research project K5/1336: 'Scale-up development of the Rhodes BioSURE® Process® for sewage sludge solubilisation and disposal'.

Table 7.1. Average best performance data for the Rhodes BioSURE Process® pilot plant study at Grootvlei Mine.

Sulphate	1900 reduced to 400 $mg.L^{-1}$
COD	3800 reduced to 200 $mg.L^{-1}$
pH	5.0/5.8 elevated to 7.8/8.2
Iron as Fe	< 1 $mg.L^{-1}$
Phosphate as P2O4	1-2 $mg.L^{-1}$
E. coli	< 100 $cfu.mL^{-1}$
Ascaris ova	0 $mg.L^{-1}$

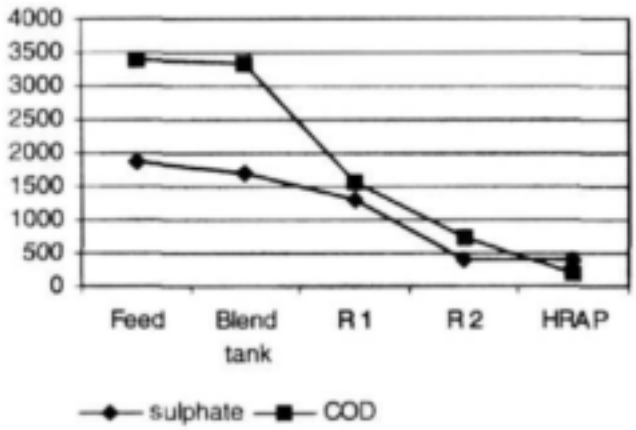


Figure 7.13. Sulphate reduction and COD consumption performance across the various unit operations comprising the Rhodes BioSURE Process®. The values represent a period of steady state performance averaged for 1 month process operation.

The sludge bed established in the RSBR (Figure 7.14) was comparable to that observed in the bench-scale studies with an upper liquid zone forming about 20% of the reactor volume, underlaid by an expanded bed of settled and settling sludge. Below this the sludge bed was composed of a dense black and somewhat viscous liquid into which the sludge floc was drawn. The falling bed was operated as a dynamic system with recirculation rates of 3-5 $volumes.day^{-1}$. With an HRT of 4.8 hours in the RSBR, a settleable solids reduction of 99% was achieved.

Solubilisation of PSS in the RSBR was reflected in a net increase in volatile fatty acids (VFA) composition. Based on a theoretical $COD:SO_4$ ratio of 0.61:1 (with COD as acetate), VFA production across the system showed an increase of 169%, where simultaneous consumption in sulphate reduction was taken into account. The VFA production values are reported in Figure 7.15 and reflect the anticipated production of VFA in the sludge hydrolysis operation occurring in the RSBR, with maximum consumption associated with sulphate reduction in Reactor 2.

In terms of overall process yield, the COD:SO_4 ratio (with COD as PSS) was close to 2:1 over extended periods of steady state operation for the pilot plant. The actual measured values for the COD:SO_4 consumption ratio in each reactor were 4.5:1 in Reactor 1 and 0.65:1 in Reactor 2. Given the close approximation in Reactor 2 to the theoretical value for COD consumption as acetate, it may be assumed that sulphate reduction in Reactor 2 was largely driven by VFA production generated in the sludge hydrolysis process in the RSBR. These values indicate a PSS conversion to acetate equivalent utilised in sulphate reduction of around 33%.

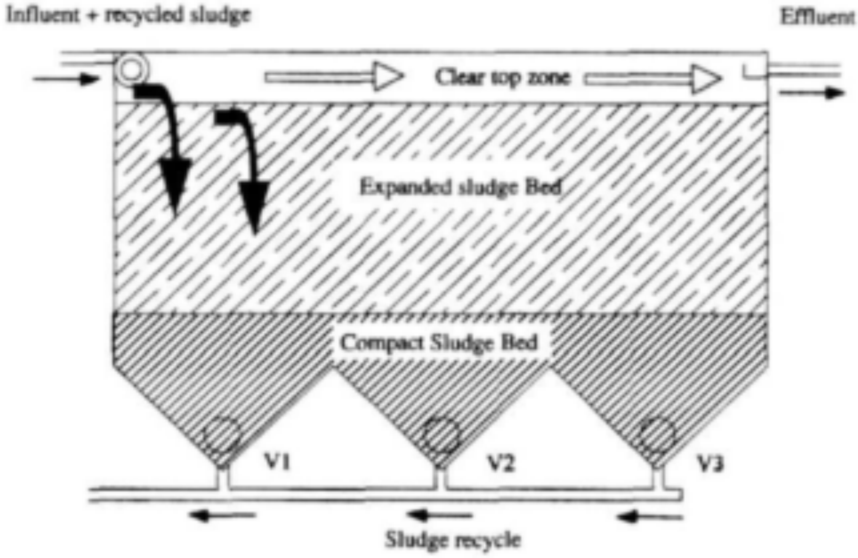


Figure 7.14. The Recycling Sludge Bed Reactor showing the segregation of settled sludge, the recycle of the sludge bed to blend with the incoming flow, and the supernatant liquid carrying the solubilised product to the second stage in the BioSURE Process®.

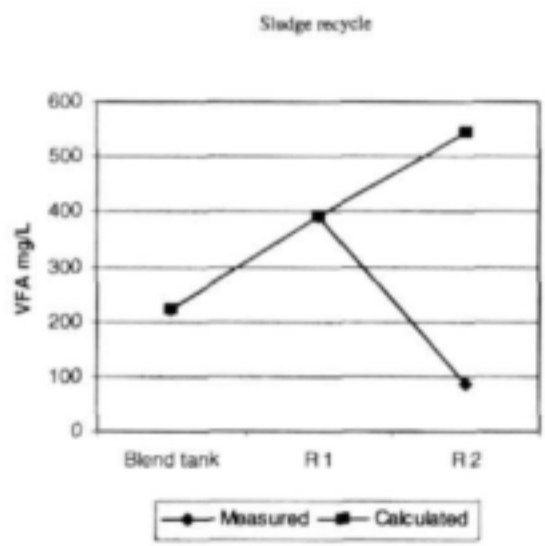


Figure 7.15. Volatile fatty acid production from primary sewage sludge in the BioSURE® pilot plant. Actual values measured across the system are compared with calculated values for total VFA production, based on COD consumed (as acetate) in sulphate reduction.

7.4.2 Follow-up Developments

The investigation of alternative carbon sources, in addition to sewage sludges, has been undertaken and has included a range of lignocellulose and maize production wastes, such as cob and stalk meals. Application of the process to treat coal mine wastewaters is the subject of a pilot study by Eskom and this project is noted in Chapter 6. The application of sulphidogenic mobilisation of complex organic substrates in passive treatment systems is described below.

Follow-up studies on the enzymology of sewage sludge hydrolysis in sulphate reducing environments has been undertaken by Prof Chris Whiteley, as a separate project in the Department of Biochemistry, Microbiology and Biotechnology at Rhodes University. Modelling of the sludge hydrolysis and the metal precipitation reactions in the process has commenced as separate collaborative projects with the UCT Chemical and Civil Engineering Departments. Modelling of the RSBR has been reported by Ristow *et al.*, (2002). The results of this work are reported in WRC Report: 'The Rhodes BioSURE Process®. Part 1: Biodesalination of Mine Drainage Wastewaters' and The Rhodes BioSURE Process®. Part 2: Enhanced Hydrolysis of Organic Carbon Substrates – Development of the Reciprocating Sludge Bed Reactor.

7.5 THE RHODES BioSURE PROCESS®: 2 – TREATMENT AND DISPOSAL OF SEWAGE SLUDGES

Sewage solids and latrine wastes have been used for millennia as soil amendments and fertilisers, and due to parasite and bacterial infections, and also heavy metal contamination, is the source of major public health and sanitation problems affecting millions of human beings today (WSSCC, 2000b). Yet in the implementation of public health programmes, removal of this nutrient resource from agricultural production, particularly in the developing world, presents a severe loss to 'closed system' and 'integrated wastewater resource management' objectives. At the same time sludges present a major disposal problem in the developed world, with few solutions remaining as landfill and marine disposal options are terminated.

Research results emerging from the AMD studies, using sewage sludge as the carbon and electron donor source for sulphate reduction and mine wastewater treatment, provided an early indication that the BioSURE Process® might also offer an efficient method for disposing sewage sludges (Figure 7.16). By manipulating sulphate and sludge ratios, the process, as described above, delivers a substantial reduction in overall solids levels in PSS. Apart from the solids reductions achieved in this way, the process also effects the precipitation of contaminating heavy metals as metal sulphides, hydroxides and possibly carbonates, and the disinfection of the feed sludges. Residual organic solids may then be disposed via biological filtration, activated sludge or similar treatment, to final land disposal as a safe humus material. Results of the study showed that fed to a HRAP system, a high grade algal biomass may be produced, and also a final water quality which meets the general standard requirement suitable for surface discharge.

Where the external sulphate source is limited and the maintenance of a sulphate inventory within the system is required, the SOBR may be used to recover S^0, oxidise it fully and return it to the process as sulphate. In principle, the primary source of sulphate could be derived from a number of industrial effluents, in addition to AMD, or from naturally occurring sulphate sources in the sewage feed.

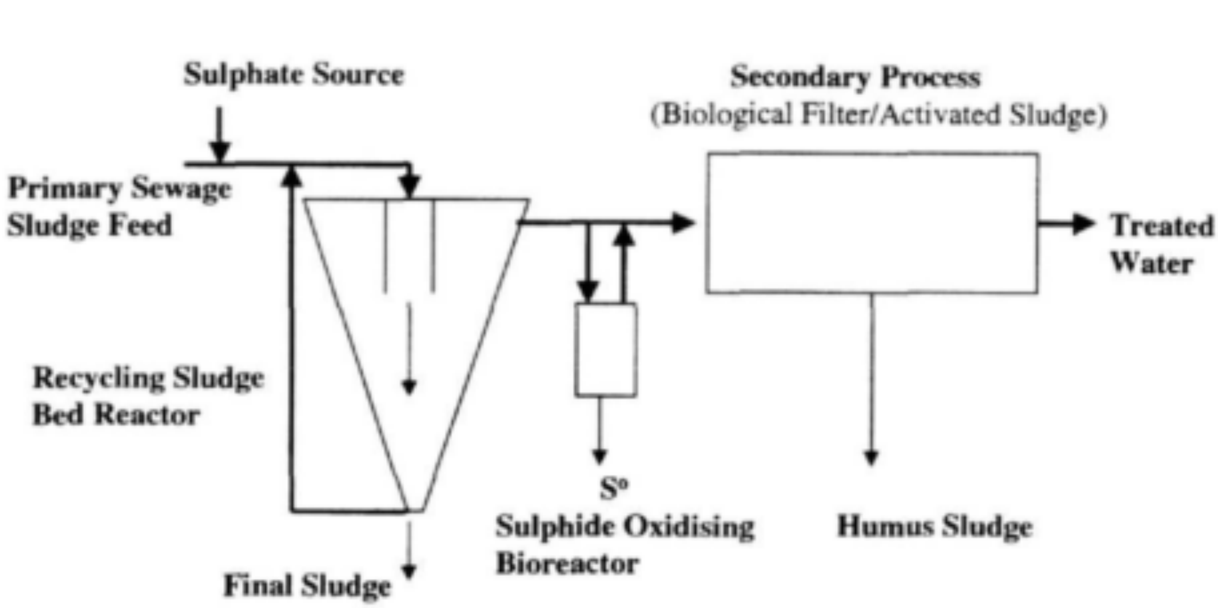


Figure 7.16. Application of the BioSURE Process® in the solubilisation of primary sewage sludge. The solubilised fraction passes from the Recycling Sludge Bed Reactor to a secondary process where organics are converted to a humus sludge, and treated water is produced. A final sludge containing metals, cysts and ova is recovered in a small volume from the Recycling Sludge Bed Reactor. Reduced sulphate may be recovered as S^0 in a Sulphide Oxidising Bioreactor.

The full-scale evaluation of the process has been undertaken by Erwat at the Ancor Works in Springs, close to the Grootvlei Mine. A technical-scale plant has been constructed on site and a pipeline has been laid from Grootvlei Mine for the delivery of high-sulphate waters (Figure 7.17). This work will be reported in WRC Report: 'The Rhodes BioSURE Process®. Part 4: Treatment and Disposal of Sewage Sludges'.

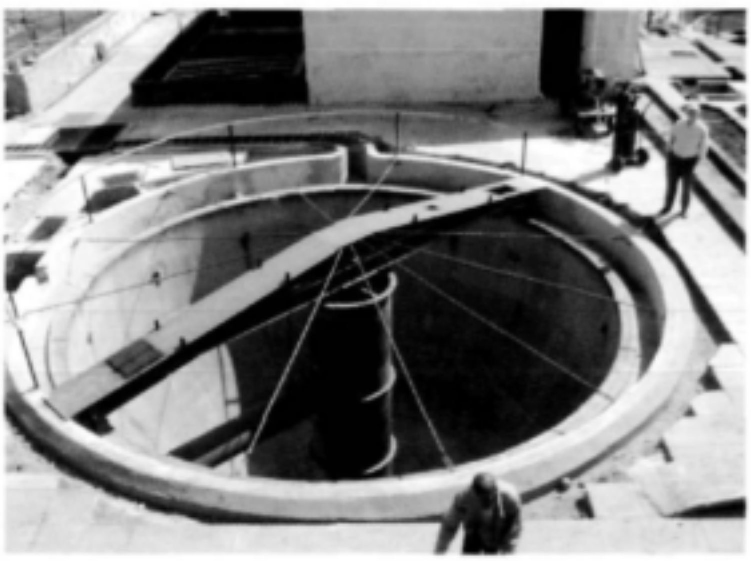


Figure 7.17. The 2 ML scaled-up Recycling Sludge Bed Reactor in the BioSURE® sewage sludge solubilisation technical-scale plant constructed at Erwat's Ancor Works in Springs. Surface struts provide supports for a covering membrane.

7.6 BIODESALINATION AND SULPHUR RECOVERY

The final removal of sulphur species is necessary to effect the linearisation of the biological sulphur cycle, and thereby provide a biodesalination of the sulphate-saline wastewater system. Where sulphidogenesis provides the initial step in the biodesalination operation, sulphide may be removed in a number of ways, including its oxidation to So. Following the final precipitation and removal of S^0 from the treated stream, it may serve as a value-added end-product of the waste treatment process.

The formation of sulphur biofilms have been observed at the air/water interface in sulphidogenic systems under specific conditions, including high soluble sulphide concentrations. These had been reported in the Wellington tannery ponding system where sulphur had been observed to occur and form thick white layers on the pond levees (Figure 7.18). The microbial ecology of sulphur biofilm formation in the Wellington tannery ponds has been investigated by the EBG. The underlying mechanisms controlling the formation of S^0 in these systems have been described by Bowker (MSc, 2002), Chauke (MSc, 2002) and Rein (MSc, 2002), and production of sulphur has been replicated under controlled conditions in the laboratory. Sulphur biofilms form at the air/water interface at high sulphide concentrations and a redox potential around -150mV. A biologically initiated production of polysulphide is catalysed by extracellular bacterial sulphur production, and this in turn leads to the crystalisation of ortho-rhombic sulphur, which may be settled as a heavy precipitate of mainly S^0 (Figure 7.19).

Figure 7.18. Floating sulphur biofims in the tannery ponds at Wellington. Biofilms of sulphur form at the air/water interface in the presence of high sulphide concentrations.

The above studies led to the development of a number of SOBR configurations which have been evaluated at both laboratory- and pilot-scale at the Experimental Field Station in Grahamstown. This development was undertaken in association with the Department of Arts Culture Science and Technology (DACST) Innovation Fund project on Passive Systems for mine water treatment described below. The Floating Sulphur Biofilm Reactor and the Silicone Tubular Bioreactor pilot plants (Figure 7.20), both operate with sulphide feed waters from an RSBR, or second stage sulphate reducing bioreactor, containing >100 $mg.L^{-1}$ sulphide. By establishing controlled redox conditions at the air/water interface a biofilm forms, the molecular microbial ecology of which has been described by Bowker (2002). Once sulphur formation commences the film develops rapidly and, at a stage, separation from the biofilm and settling commences. Harvesting of the film is managed to recover a maximum settleable sulphur precipitate. Results of this work will be reported in WRC Project: 'The Rhodes BioSURE Process®. Part 3: Sulphur Production and Metal Removal Unit Operations'.

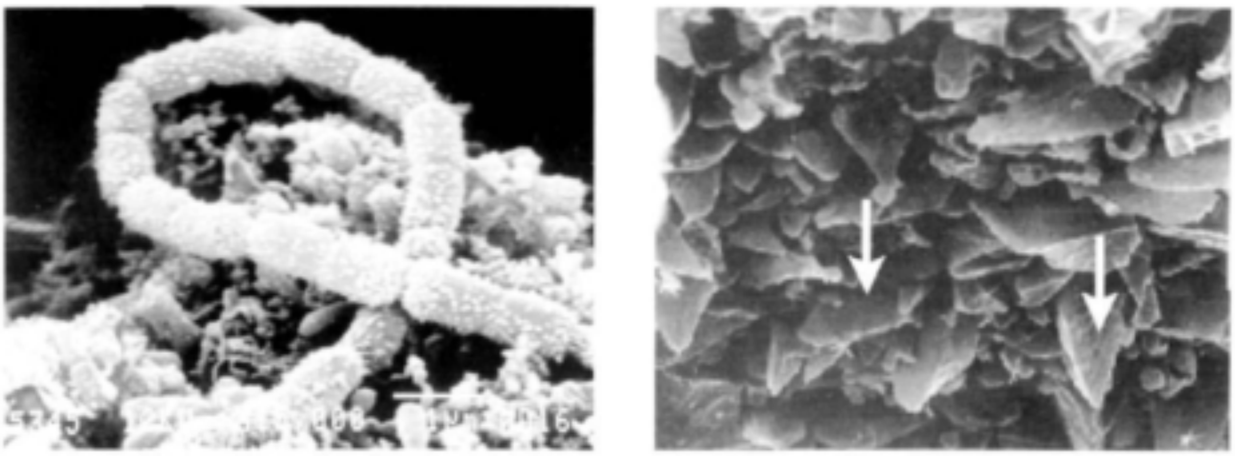


Figure 7.19. Bacterial extracellular sulphur catalyses the formation of polysulphide in the presence of sulphide at redox values around -150 mV. At the air/water interface this is followed by the crystalisation of ortho-rhombic sulphur.

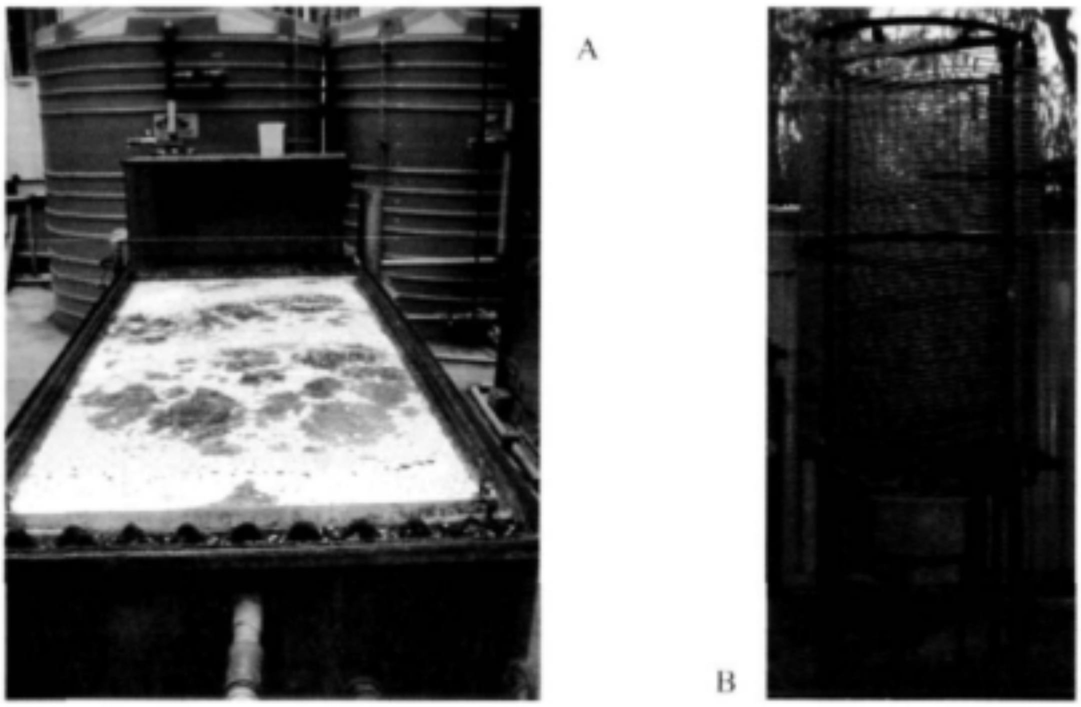


Figure 7.20 The Floating Sulphur Biofilm Reactor (A) and the Silicone Tubular Sulphur Bioreactor (B).

7.7 PASSIVE TREATMENT SYSTEMS

While the active treatment of mine dewatering wastewaters is practised in most operating mines, the need to demonstrate long-term sustainable treatment following the termination of these operations, has become a prime requirement for achieving formal mine closure certification. This has placed increasing focus on the use of passive treatment systems, which require minimal maintenance and involve no moving parts. A WRC study in this area, undertaken by consultants Pulles Howard & De Lange, became the subject of a major DACST Innovation Fund grant, in 1999, to progress the technology to market implementation.

The EBG contribution to the Innovation Fund study included an investigation into the use of lignocellulose as a complex carbon source in sulphate reduction. The development of a lignocellulose packed bed reactor was undertaken based on insights derived from the BioSURE® studies in the enhanced hydrolysis of complex organic carbon substrates (Madikane, MSc 2002).

Basic studies in the molecular microbial ecology of the biosulphidogenic lignocellulose environment had shown that bacterial action in the mobilisation of particularly the lignin in the anaerobic environment, a surprising finding in itself, was dependent on the establishment of initial conditions in the first stage of the reactor. These included oxygen consumption in the feed stream, production of fermentation products from simple carbon sources, poising of the redox potential and initiation of sulphate reduction and alkalinity production. Following this, phenol degrading bacteria were found to predominate, and in breaking down the lignin molecule enabled access to cellulose by rumen-type cellulose degrading bacteria. This process resulted in the production of a range of VFAs which were used as electron donors by the SRB in sulphate reduction.

Experimental wood chip-packed column reactors were operated as upflow units in the Pulles Howard & De Lange laboratories in Johannesburg, and the description of the processes involved is outlined in Figure 7.21.

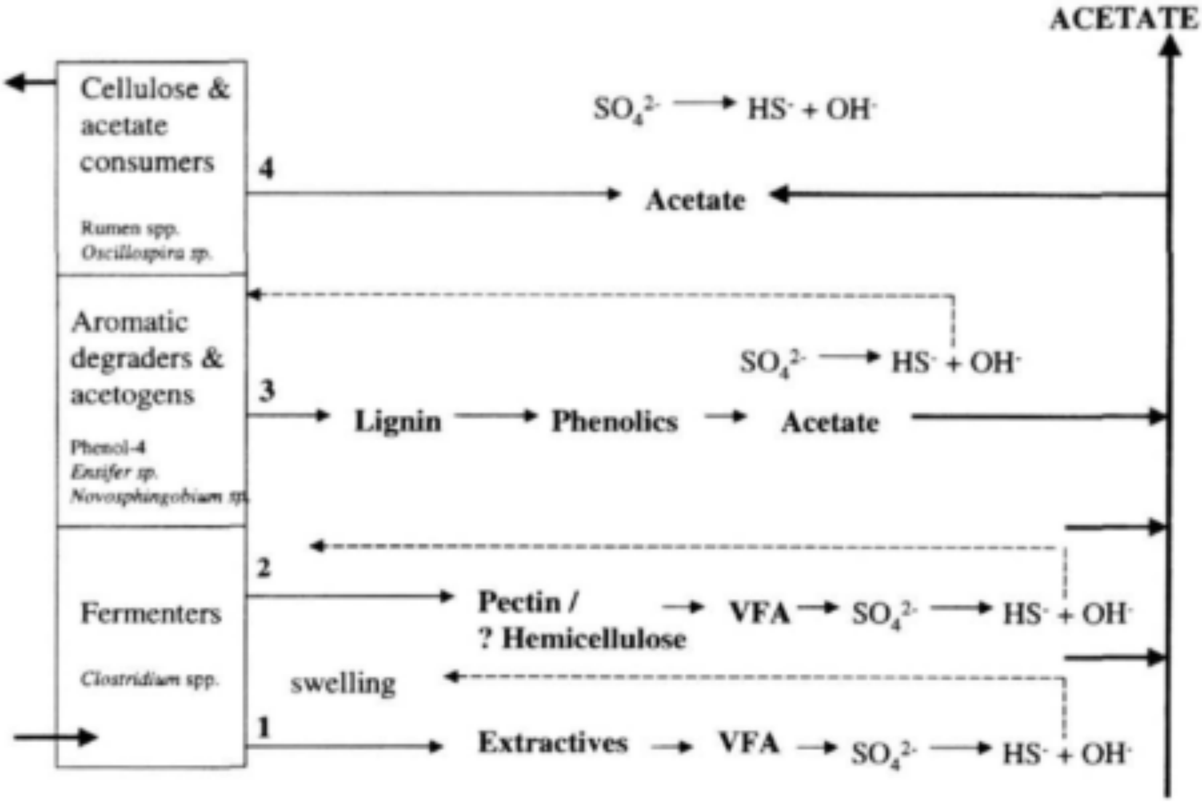


Figure 7.21. A descriptive model of events occurring in the mobilisation of lignocellulose as carbon and electron donor source in experimental wood chip packed columns. A molecular microbial ecology study of the system provides an explanation of processes occurring at each level.

The study led to the development of the Degrading Packed Bed Reactor (DPBR), where a carbon recharge zone is used to establish and maintain the required initial conditions (Figure 7.22). The VFA-rich stream passes to a second reactor where sulphate reduction is optimised and final biodesalination is achieved (Pulles and Rose, 2002). The study also undertook a detailed examination of the SOBR and its application in sulphate removing Passive Systems.

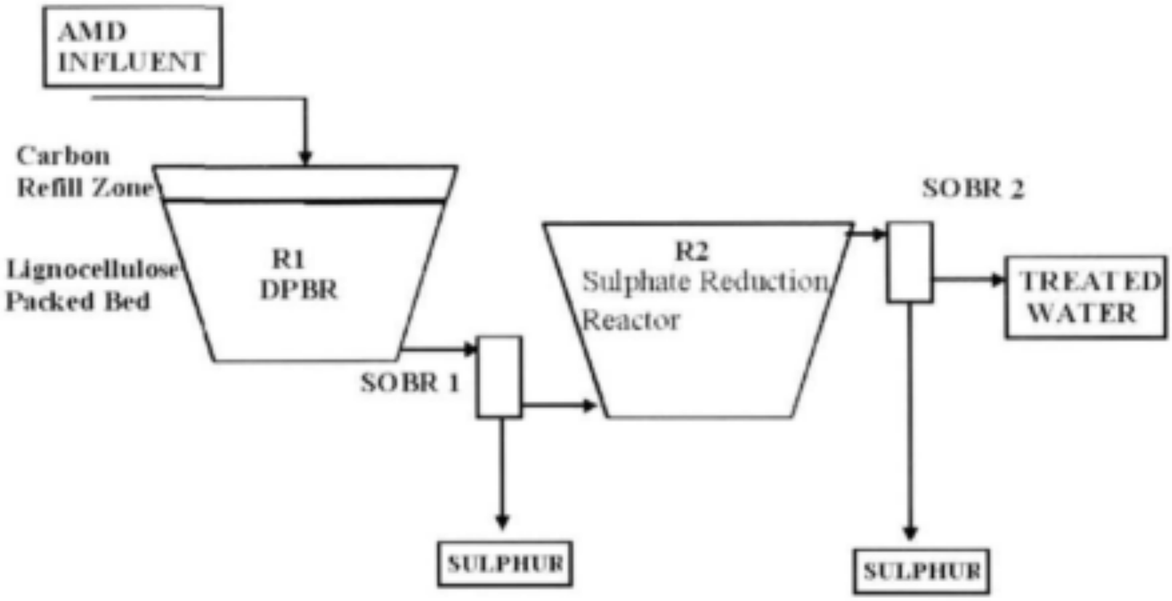


Figure 7.22. The two stage system for Passive Treatment of sulphate-saline mine wastewaters including the Degrading Packed Bed Reactor (DBPR) and its carbon recharge zone, the Sulphate Reduction Reactor unit, and the Sulphide Oxidising Bioreactor (SOBR). Treated water and sulphur are produced as final products.

7.8 CONCLUSIONS

The development of the ASPAM and Rhodes BioSURE® processes for the treatment of sulphate-saline wastewaters developed from preliminary studies related to IAPS applications in tannery wastewater treatment. These studies not only showed the potential value of ponds as effective bioreactors in the treatment of sulphate-saline wastes in potentially large volume flows, but also, surprisingly, that the hydrolysis of complex particulate organic wastes may be enhanced in biosulphidogenic systems. Also, that a wide range of organic wastes may be used to provide efficient electron donor sources for SRB-based bioprocess development.

Although these studies appear to have wide ranging implications in a fundamental understanding of basic processes in environmental nutrient cycling, the results also showed that the mechanism involved may be engineered to effect the co-disposal of PSS in AMD treatment. Process development from bench-scale to pilot plant studies showed that PSS can be solubilised under sulphate reducing conditions to yield a hydrolysed product of around 33% VFA, calculated as acetate. This may be used directly in a second stage operation for sulphate reduction. Where sewage sludge disposal is required, the solubilised fraction may be disposed to a downstream unit operation such as a biological filter or activated sludge process. Here a humus sludge will be the final product. Sludge hydrolysates produced in this way might also be used in nutrient removal tertiary treatment operations.

Sulphur recovery from the oxidation of sulphide produced in the process provides for the final biodesalination of the treated stream. It was shown that alternative carbon sources such as lignocellulosic wastes may be employed, and that the enhanced hydrolysis reactions may be used to mobilise a SRB feedstock from this source.

The linkage of the sulphate-saline and sanitation systems provided in the BioSURE Process® not only offers a mechanism for enhancing water resource sustainability, especially in the Vaal River catchment which receives large volumes of both mining and sewage wastewaters, but provides for a process by which two problematic waste streams might be beneficiated. Scale-up application of these studies is under active evaluation at this time (2002).

8 THE DEVELOPMENT AND ENGINEERING OF IAPS APPLICATIONS

In certain aspects of its brief, environmental biotechnology occupies a pre-engineering phase of innovation in the technology development chain. Many of the insights emerging from studies in this area, and the development of potential applications feeding into bioprocess research, are derived from enquiries relating to fundamental mechanisms in biology. To be effective, the interface between the idea, its development, and its final construction on the ground as a finished engineered process or product, requires a collaborative application of skills drawn from a range of disciplines.

The development of the IAPS approach to the sustainable management of saline wastewaters raised many of these problems. The sequence of bioprocess innovation and development undertaken in these studies, particularly with respect to ponding systems, required the simultaneous development of the engineering base, if these were to prove more than a collection of interesting ideas. This objective was partly met by the technology transfer project in which an IAPS demonstration and research plant was constructed in South Africa. The objectives of this initiative included not only the provision of a model system on which to base particular aspects of the saline wastewater treatment developments described here, but also to simultaneously assist technology diffusion in the application of the system as an appropriate technology for low-cost sewage treatment, and related uses.

As already observed, integrated ponding systems, as applied to wastewater treatment, have been under development in many parts of the world, including South Africa, since the 1950s. A rather confusing range of terms has arisen over this period to describe variants of these systems, including different arrangements of the terms integrated, algal, high rate, oxidation, wastewater and ponds. At the outset of these studies, the term Integrated Algal High Rate Oxidation Ponds was used, but was found to be inconsistent with prior descriptions of particular ponding process developments, and hence a possible source of additional confusion. Without debating the merits of the different forms, the IAPS has been used here as a generic description of a particular configuration of integrated ponds incorporating the optimisation of anaerobic processes in an advanced facultative pond and of algal processes in HRAP raceway structures. The AIWPS represents the final trade mark product of the Oswald developments at UC Berkeley's Institute of Engineering Research – previously the Sanitary Engineering and Environmental Health Research Lab of the Richmond Field Station.

8.1 IAPS IN DOMESTIC WASTEWATER TREATMENT: THE AIWPS MODEL

The development of IAPS has been the subject of ongoing development and refinement based on a process development initiative which was initiated by Professor William Oswald in the 1950s (Oswald *et al.*, 1957; Oswald and Golueke, 1960). Oswald recounts his thinking at that time: "In conventional wastewater treatment, solids from primary and secondary sedimentation are put into a digester for 40 days. They are then removed, dried, and buried. Why not bury them in the first place? The conventional digester 40-day residence time does not permit complete digestion. It only conditions the sludge to drain and dry quickly. Why not build a Parker-type, deep pond with a volume big enough so that all the settled solids can remain and digest for hundreds of days, and put that pond inside a bigger pond where algae could grow and produce oxygen to destroy odours? Why not then have a second pond where algae are grown under optimal conditions of light and mixing? When algae are grown under such conditions, they increase the pH and produce dissolved oxygen. So why not recycle this oxygen for disinfection and odour control? Then settle and remove the algae for use as a fertilizer or animal feed. Finally, why not add maturation ponds for further disinfection prior to discharge or reclamation." The Advanced Integrated Wastewater Ponding System (AIWPS) was the result of nearly 40 years of developments surrounding the concept (Oswald, 1995).

While the treatment objectives of the individual unit processes of the AIWPS do not differ greatly from those of conventional plants – primary sedimentation, flotation, fermentation, aeration, secondary sedimentation, nutrient removal, storage, and final disposal – the system utilises the integration of anaerobic and aerobic biological processes in a unique configuration of ponding system applications. Ponds not only provide low-cost reactors, at least an order of magnitude cheaper than concrete structures (Oswald, 1995), but algal photosynthesis yields large quantities of oxygen to support bacterial breakdown of the organic components. Shelef (1987) has noted that IAPS epitomises the principles of water and nutrient recycling, and closes the cycle of waste to primary biomass more rapidly than any other outdoor process converting organic wastes into an algal biomass rich in protein, while stripping out nutrients. Furthermore all this is accomplished without mechanical aeration but capitalising only on solar energy and, following algal harvesting, producing a high quality effluent not surpassed in quality by other biological or physico-chemical wastewater treatment processes.

8.1.1 Aims

The study reported here formed the basis of the WRC Project K5/651: 'Appropriate low-cost sewage treatment using the integrated algal high rate oxidation ponding process'. The principal objectives of the project were:

- ❑ The building and operation of an integrated high rate oxidation pond (IAPS) for the treatment of domestic sewage. This demonstration plant would aim to effect the transfer of currently best available technology world-wide on the design, construction and operation of these systems, with specific application as appropriate technology, and low-cost systems for small and developing communities;
- ❑ To evaluate the manipulation and control of algal and bacterial growth and species dominance in the IAPS system;
- ❑ The recovery of algal metabolites and other products of value from the micro-organisms in the IAPS system.

8.1.2 Results

Following a number of overseas visits, and meetings of WRC researchers, it was agreed that the AIWPS approach provided, in many respects, the most mature model on which a process of bioprocess innovation relating to IAPS may be based (Figure 8.1).

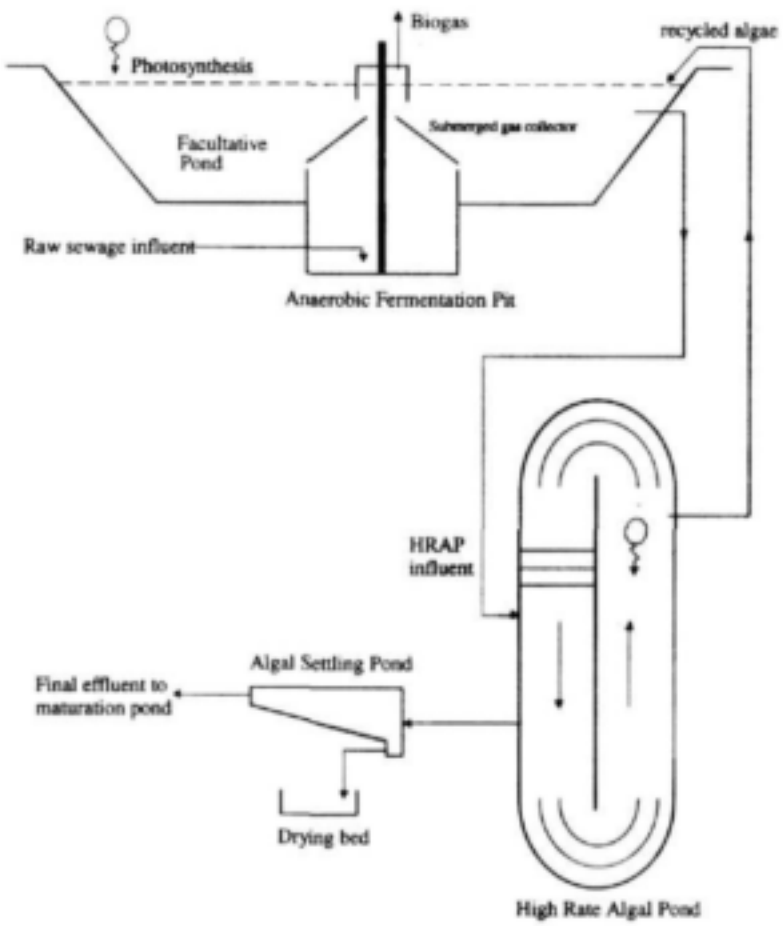


Figure 8.1. Schematic diagram of the IAPS demonstration and research plant constructed at the Environmental Biotechnology Field Station in Grahamstown as a component of the IAPS research facility.

Following a visit to California by the author in 1992, and later by WRC Research Manager Dr Oliver Hart, Professor Oswald visited South Africa in May 1993 at the invitation of the WRC to lecture on the principles of IAPS at various venues. During this visit it was decided that Rhodes University would submit a proposal to the WRC for the funding of an IAPS demonstration plant, to be constructed at the Grahamstown municipal wastewater treatment plant. Professor Oswald would undertake the technology transfer process in association with Mr Peter Ellis of Murray Biesenbach and Badenhorst, Engineering Consultants in Grahamstown, and supported by Mr Piet Meiring of Wates, Meiring and Barnard, Pretoria. Professor Oswald visited South Africa again in January 1994 to attend the International Anaerobic Digestion Conference in Cape Town. During this visit Professor Oswald was joined by his senior research associate, Dr Bailey Green, during which period process designs and plans for the plant construction were finalised.

Construction design drawings were prepared by Mr Ellis, and construction of the plant was undertaken by Civil and General Construction Co., Queenstown, South Africa. The design and construction phase was completed in February 1996, and the first water flowed into the new plant on the 27th of that month (Figure 8.2). Following commissioning of the plant, the debugging of problem areas, and the establishment of stable operating conditions, all of which took place over a 6 month period, a process of performance monitoring of the system commenced. The plant was officially opened on 18 April, 1997, by The Honourable Minister of Water Affairs and Forestry, Prof Kader Asmal (Appendix 3.1).

This study is the subject of WRC Report 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 1: The AIWPS Model'.

Figure 8.2. The Primary Facultative Pond and High Rate Algal Ponds of the AIWPS process constructed at the Grahamstown IAPS demonstration and research plant treating domestic wastewaters.

8.1.3 Conclusions

While the principal objectives of the project were achieved with the construction of the plant (Aim 1), the time allocated to technology transfer, design, construction and commissioning did not allow the accumulation of an adequate data base relating to operational experience by the end of the project period (December,1996). Numerous problems were encountered, including adaptations of the system to particular requirements unique to application in South African operating conditions. In addition the study revealed opportunities for improving the original concept and making a substantial and fundamental contribution to the technology of both the AIWPS specifically, and applications of IAPS in a general sense.

In order to undertake both the monitoring objectives identified at the outset of the project, and also the process development objectives which had become apparent during the course of research being undertaken in the EBG, the WRC awarded the Projects K5/799: 'Development and monitoring of integrated algal high rate oxidation pond technology for low-cost treatment of sewage and industrial effluents'; and 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'. These projects ran from 1997 to 2001, and provide a 5 year performance evaluation of the AIWPS process, in addition to a number of process developments and applications. These studies are reported in the WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 4: AIWPS System Performance and Tertiary Treatment Operations'.

This development has resulted in an iterative process of research development, including findings and insights which have made substantive inputs into a number of associated projects, including IAPS for the treatment of tannery wastewaters (K5/495), abattoir wastewaters (K5/658), mine drainage wastewaters (K5/869; K5/972; K5/1078), and the treatment and disposal of sewage sludges (K5/1169). While each of these projects is the subject of a separate report, the K5/799 and 1073 initiative also produced findings which have led to the development of the HRAP as a free-standing water treatment unit operation, the Independent HRAP (I-HRAP). The I-HRAP may be used in a number of applications, including tertiary treatment nutrient removal operations and the renovation of raw waters, particularly in the context of the sustainability of water resources in the developing world.

Recovery of biomass from the HRAP, and its evaluation as a feed in aquaculture rations was undertaken in the Department of Ichthyology and Fishery Sciences at Rhodes University. The results of this study are reported by Potts (1998), and led to a conceptual plan to construct an integrated water treatment aquaculture operation in Grahamstown, as an SMME development in this community. Algal biomass recovered from the HRAP, and treated water, would be used as inputs to the aquaculture enterprise and the IAPS would be used to treat its effluent wastes. The results of this initiative in 'integrated wastewater resource management' will be reported elsewhere.

8.2 THE I-HRAP: AN INDEPENDENT HRAP UNIT OPERATION FOR TERTIARY TREATMENT AND THE RENOVATION OF RAW WATERS

The quality of water available to rural communities has been declining consistently over the past 30 years, and nearly 10 years ago Lusher & Ramsden (1992) noted that water, in its natural state, was becoming increasingly unavailable for use in the third world context. Despite significant progress in the provision of water supply in rural areas, substantial numbers of people are still without supply (Kasrils, 2002). In addition to contamination by heavy metals and organic pollutants, microbiological contamination and pathogen loads commonly reach unacceptable levels, with severe consequences, particularly for disadvantaged communities. Many rural communities are entirely dependent on surface water for their domestic needs and have no opportunity to pre-treat it in any way before consumption.

While diffuse sources of contamination due to inadequate sanitation is well described, one of the other contributing causes to the poor quality of rural surface waters is the small sewage treatment works handling domestic and/or industrial wastewaters. Periodic malfunction in these works is common, often due to overload and operational problems, and results in an inability to meet surface water discharge standards. Where neither plant replacement nor upgrading of the existing facility can be afforded, the problems of surface water quality may go largely unaddressed with severe consequences for downstream users.

The study reported here undertook the development of the I-HRAP, a free-standing unit operation independent of the IAPS, or indeed other treatment systems. The development focussed on the treatment of dilute feed waters where a minimum level of nutrients remain in the water, sufficient to sustain algal growth. These may be final discharge waters from a sewage treatment works, requiring nutrient removal and polishing, or raw water abstracted from an open water source, and passed to treatment through a HRAP unit prior to consumptive use (Clark, MSc 2002).

The array of factors available in the HRAP, including algal biomass production, elevated alkalinity, high light penetration, high oxygen concentrations, and possibly also free radical oxygen generation, combine to provide suitable conditions in which the disinfection and tertiary nutrient removal treatment of feed waters may be manipulated.

8.2.1 Aims

This study reports a particular component of WRC 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'. The following is the principal aim of this project, and forms the subject of a separate report:

- ❑ To develop the application of the HRAP as a free-standing tertiary treatment unit operation for the removal of nitrates and phosphates from conventionally treated sewage effluents.

8.2.2 Results

The detailed results of this study are reported in WRC Report: 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 4: AIWPS System Performance and Tertiary Treatment Operations'.

Following preliminary laboratory studies, a technical-scale investigation was undertaken at the Environmental Biotechnology Experimental Field Station in Grahamstown, and used one of the 500 m^2 HRAP units of the IAPS pilot plant (Figures 8.3 and 8.4). Feed water was sourced from the Grahamstown Works, and high coliform counts, and nitrate and phosphate levels between 15 and 30 $mg.L^{-1}$, made this stream suitable for the study.

8.2.2.1 Phosphate Removal

The I-HRAP is operated in a manner in which a high pH is established, due to algal photosynthetic activity, and is maintained around pH 9.5 (Figure 8.5). At calcium concentrations >15 $mg.L^{-1}$, phosphate removal is principally in the form of calcium phosphate precipitation in the HRAP, and the process may be further manipulated by the addition of calcium in various forms. Phosphorus assimilation by algal biomass might occur as a secondary phenomenon. The high pH environment also facilitates removal of excess ammonium nitrogen by stripping effects.

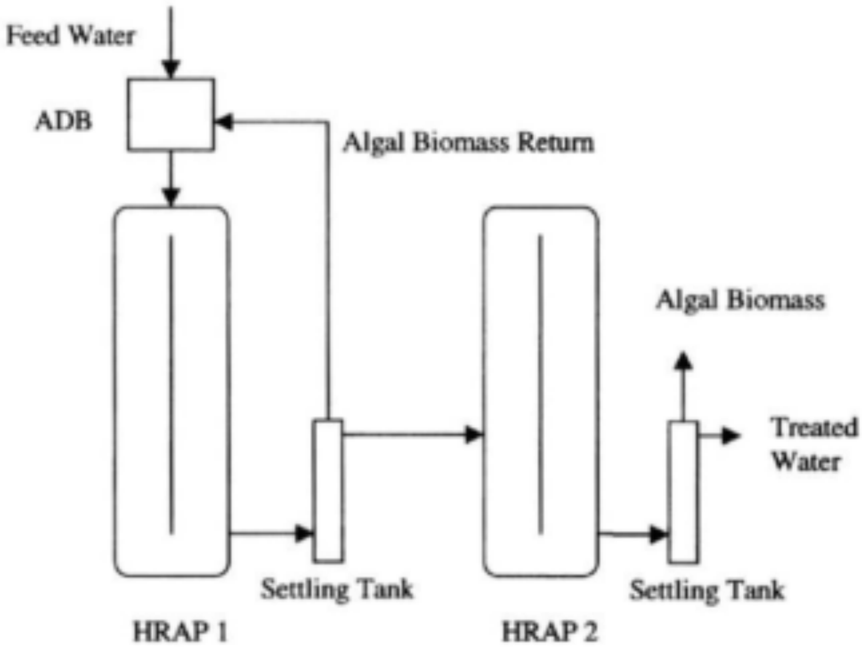


Figure 8.3. Configuration of the Independent-High Rate Algal Pond (I-HRAP) for Nitrogen and Phosphate removal. Influent water and algal biomass, recycled as the carbon source, passes through the Algal Denitrification Bioractor (ADB). Phosphate removal occurs in both HRAP 1 and 2.

The HRAP is followed by an algal settling tank or some other method of removing algal biomass from the HRAP effluent, together with excess calcium phosphate solids. Phosphate removal to below 1 mg.L^{-1}, has been sustained over prolonged periods of the I-HRAP operation study.

Figure 8.4. The Independent High Rate Algal Pond (I-HRAP) unit operation for tertiary treatment and the renovation of raw water at the Environmental Biotechnology Field Station, Grahamstown. The I-HRAP is in the foreground with the Algal Denitrification Bioreactor (ADB) column and the algal settling tank behind.

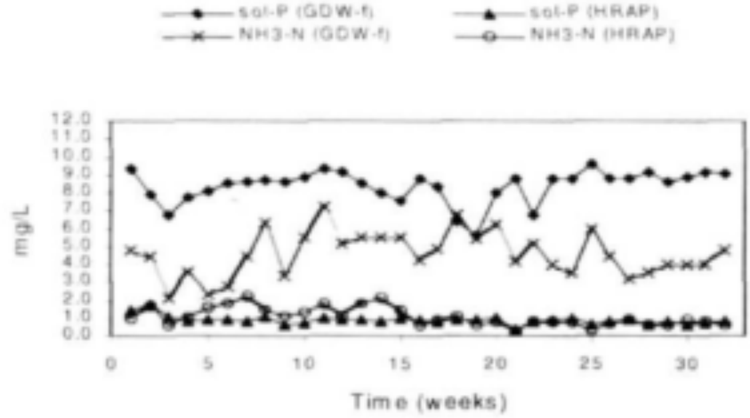


Figure 8.5. Ammonia and phosphate removal in the I-HRAP units over a 35 week operational period.

8.2.2.2 Denitrification

Anoxic denitrification is the reduction of nitrate (NO_3^-) to nitrogen gas (N_2), and is a heterotrophic process performed by a variety of facultative anaerobic organisms. An appropriate carbon source is required, the cost and availability of which presents a real limitation in applying biological denitrification in the context of the small treatment works.

This development examined the use of algal biomass derived from an HRAP as the carbon source for denitrification, and involved the development of the Algal Denitrifying Bioreactor (ADB). The ADB is a reactor sequence in which the algal biomass is partly broken down, releasing small molecular weight compounds which are made available to the denitrifying bacteria. The bacterial population may be retained in the same unit or as an attached biofilm in a second stage anaerobic trickle filter (ANTRIC). Where the second stage ANTRIC is used, the algal carbon source is blended into the nitrate containing feed water to be treated, at a concentration related to the nitrate removal required. Removal levels from around 30 $mg.L^{-1}$ to 1 $mg.L^{-1}$ have been sustained over prolonged periods of operation of the ADB.

Where any HRAP-produced algal biomass may be used in the ADB operation, it is important that this not be drawn from an I-HRAP used for phosphate removal, given P release under conditions of increasing anoxia and falling pH levels. Where both N and P removal is required in the I-HRAP operation, two HRAP units are needed – one providing primary treatment, partial alkalisation and disinfection, and algal biomass production for the ADB; the other to complete alkalisation and P removal. Biomass recovered from the second reactor is not used for N removal, but may be disposed as fertiliser, feed or any other appropriate application.

8.2.2.3 Disinfection

A high level of disinfection of enterobacteria has been observed in the I-HRAP. In a 3 day hydraulic retention time (HRT), coliform counts have been reduced by three orders of magnitude, and entrobacteria completely eliminated. Algal flocs in the I-HRAP are quite tightly condensed, allowing a high level of light penetration into the surrounding water column. Given the relatively low organic loading to the system (COD <100 $mg.L^{-1}$), oxygen levels remain high at around 80% to 300% saturation, during both day and night time operation. These factors together with UV light penetration are thought to account for the effective disinfection observed.

8.2.3 Conclusions

This study has demonstrated the development of the I-HRAP through laboratory studies, and scaled-up to a technical-scale evaluation in a 500 m^2 HRAP unit. Where the process combines the ADB, N and P removal in addition to disinfection of feed waters may be achieved in a low-maintenance, low-cost operation, appropriate to applications in the small community or development environment. It also provides a low-cost system whereby small community systems can achieve general standards for discharge of treated water to the public water system.

In meeting these needs, the IAPS provides a 'core technology' which is both upgradeable, and its unit operations applicable across a range of water treatment needs.

8.3 THE IAPS IN ABATTOIR WASTEWATER TREATMENT

Abattoirs produce large volumes of high-strength organic wastewaters, which present significant environmental problems due to the COD, total Kjelhahl nitrogen (TKN), phosphate, protein and specifically blood constituents. Average water usage is estimated at around 1.3 $m^3.wrcu^{-1}$ (water related cattle unit), and about 82% of water intake is returned as industrial effluent. Since abattoir effluents require a very high degree of treatment, it is normally with great difficulty that the General Standard for discharge to the public water system is met. In addition, due to high sewer discharge costs, it is usually necessary to effect some form of treatment on-site (Steffen, Robertson and Kirsten, 1990).

A more recent development in the South African meat industry has been the increasing shift of stock slaughtering to smaller country abattoirs. This move creates additional problems in terms of diffuse effluent treatment and, in common with much of the developing world, an urgent need exists for the development of appropriate, low-cost, low-maintenance abattoir wastewater treatment systems.

The study reported here commenced in 1995 in association with Abakor, then the largest single abattoir operator in South Africa with interests in 14 abattoirs, and processing about 40% of the commercial slaughter in South Africa.

8.3.1 Aims

The study reported here formed the basis of the WRC Project K5/658, 'Algal high rate oxidation ponding for the treatment of abattoir effluents'. The research products were identified as low-cost treatment for abattoir effluents, with medium and small-sized abattoirs as the target group. The project targeted three principal objectives:

- A laboratory study to evaluate the function of the Algal High Rate Oxidation Ponding process applied to the treatment of abattoir effluents;
- Scale-up evaluation of rate functions for the process in a 5 m^2 outdoor pilot plant facility under semi-laboratory conditions. Both total combined effluent and polishing of partly treated effluents to be evaluated;
- Construction of a 500 m^2 demonstration facility on-site at Cato Ridge Abattoir.

8.3.2 Results

The results of this study are detailed in the WRC Report, 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 2: Abattoir Wastewaters'.

The project commenced in 1995, with laboratory studies undertaken by the EBG evaluating the growth of *Spirulina* and mixed micro-algal cultures, in various formulations of effluent supplied from Cato Ridge Abattoir. It was shown that both cultures acclimatised to growth in diluted forms of abattoir effluent, and that this growth may be associated with substantial reductions in organic load achieved.

The study was then scaled-up using a bench-scale IAPS unit, a 270L system constructed in polypropylene (anaerobic pit – 11L; primary facultative pond – 169L: and 2 HRAP – 50L each). Effluent was sourced from the Port Elizabeth abattoir, the anaerobic pit was seeded with sludge from the Grahamstown Disposal Works anaerobic digester, and adapted *Spirulina* cultures were used to innoculate the system.

Following a process of incremental loading, an HRT of 30 days was established for the system, with overall COD reductions of 91-94% (COD in = 6443 $mg.L^{-1}$). COD reductions in the pit averaged around 65%, with biogas production measured at 0.1 $L.g^{-1}$ COD removed. Following the bench-scale pilot plant studies, a technical-scale plant was constructed at the Cato Ridge Abattoir (PFP = 864 m^2 ; HRAP = 500m^2), with an average organic load in the feed water of between 2500 and 3500 $mg.L^{-1}$ COD. The pilot plant was constructed and commissioned at the end of 1995 (Figure 8.6).

Figure 8.6. The High Rate Algal Pond unit operation of the IAPS plant constructed at the Cato Ridge Abattoir for the treatment of abattoir wastewaters.

The plant was operated for a two year period and following stabilisation, a good average treatment performance was established at an HRT of 30 days. The following removals and effluent discharge levels were recorded for best operating conditions: COD = 90-95% (215 $mg.L^{-1}$); ammonia = 97% (1.5$mg.L^{-1}$); phosphate 95% (1.1$mg.L^{-1}$).

8.3.3 Conclusions

The project demonstrated the effective scale-up development of the IAPS in the abattoir wastewater treatment application. While the aerial loading to the system of around $30m^2.m^{-3}.day^{-1}$ effluent feed is average for IAPS systems, it is apparent from the study that the process would be best applied in medium-sized to small abattoir operations. Nevertheless, given the relatively high quality of the effluent produced, which can be even further improved by the incorporation of a maturation pond following the HRAP, the system would be particularly suitable for the country abattoir discharging directly into the public water system.

This application also demonstrated the upgradeability potential of the IAPS. The use of a common technology for both domestic and industrial wastewater treatment provides for the growth of small communities as they develop economically from subsistence to manufacturing production enterprise.

8.4 THE IAPS IN WINE AND DISTILLERY WASTEWATER TREATMENT

Wine and spirit producers are both major generators of wastewaters, with distilleries discharging a high COD (> 35 000 $mg.L^{-1}$) and saline (> 2000 $mS.m^{-1}$) wastewater of up to 6.2 $m^3.m^{-3}$ spirit produced (Steffen, Robertson & Kirsten, 1993). Distillation slops and wine lees, the fermentation precipitate of grape skins, pips and yeasts, is processed for tartaric acid recovery and adds further to the saline COD load.

Disposal of these wastes is a problem, particularly in the highly salinised Western Cape rivers. The use of ponding systems for winery wastes has been considered (Torrijos and Moletta, 1998), but high strength distillery and wine lees wastes remain a problem for which land disposal has presented one of the few outlets.

This study investigated the use of IAPS in distillery and wine lees wastewater treatment. Following an initial COD knock-down in an ABR, the partly treated water would pass via a Facultative Pond and HRAP to a solar evaporation cascade where a range of meso- and hyper-saline algal species would be produced (Figure 8.7). Apart from linearising the salt removal operation, both yeast and algal biomass might be incorporated into high-value aquaculture production.

This study was undertaken in collaboration with Brennokem Co. in Worcester, South Africa, and as a component of WRC 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'. It will be reported in detail in WRC Report 'Integrated Algal Ponding Systems and the Treatment of Domestic and Industrial Wastewaters. Part 5: Winery and Distillery Wastewaters'.

Following laboratory studies in Grahamstown, a pilot plant was constructed and erected on-site at Brennokem Co. in Worcester, and operated over a two year period (Figure 8.7). An effective COD and phosphate removal of around 97% was demonstrated. The need to regulate ammonia toxicity in the anaerobic process was identified as an important control variable in this system. Fish feed utilisation studies were undertaken by the Rhodes

University Ichthyology Department and showed that both waste yeast and algal biomass provided high grade aquaculture rations for fish production.

Figure 8.7. Pilot plant at Brennokem Co., in Worcester, South Africa, evaluating the IAPS in the treatment of wine lees and distillery wastewaters.

This study presented another useful model for the application of IAPS as a versatile low-cost upgradeable wastewater treatment system. The results showed that the technology could be applied to the needs of the small business agro-industrial enterprise, in addition to previously demonstrated domestic wastewater treatment, with minimal additional investment in construction techniques, operational skills and training. The potential beneficiation of these wastes in algal and aquaculture production presents a further example of the broad potential available in 'integrated wastewater resource management'.

8.5 CONCLUSIONS

The development of the IAPS applications outlined here has provided a technology base to underpin a wide range of wastewater treatment applications, and specifically enabling a linkage of the salinity and sanitation systems.

The construction and operation in Grahamstown of the IAPS demonstration and research plant, in collaboration with Oswald and Green, provided for both a technology transfer and technology development initiative. This development served to inform a range of applications in the salinity and sanitation studies including saline tannery wastewater treatment (Wellington), hyper-saline alkaline waters (Sua Pan, Botswana), mine water treatment (Grootvlei, Springs), saline wine lees and distillery wastewaters (Worcester), and abattoir wastewaters (Cato Ridge). Apart from meeting technology diffusion needs, the process of indigenous technology development has also contributed to the development of human resources needed to make a contribution in the general area of wastewater treatment and environmental biotechnology.

9 CONCLUSION. ACHIEVING SUSTAINABILITY THROUGH AN INTEGRATED BENEFICIATION OF THE WASTEWATER RESOURCE

The WRC study in 'Salinity, Sanitation and Sustainability' was conceptualised as a research initiative in the late 1980s and early 1990s within the context of the emerging sustainable development debate, and this has informed many of its underpinning objectives over the subsequent twelve years of the study.

Salinity and sanitation had long been identified as priority pollution and waste issues, and together with increasing awareness of the limitations of the national water resource, and also the immense human development tasks facing the country, had emerged as important issues among the broader goals of sustainability in the Southern African region. This early prioritisation had been confirmed in subsequent environmental assessments emerging during the 1990s.

The potential application of developments in algal biotechnology, which had emerged as an active research field over the 1970s and 1980s, to deal with specific aspects of local salinity and sanitation problems, had been noted. Shelef (1987) had observed that algal ponding systems are able to close the cycle of waste to biomass more rapidly than any other outdoor water treatment process, and Oswald (1988a) had identified the HRAP as the most efficient way known to fix solar energy in the form of biomass. The efficiencies of ponds as bioreactor vessels had been identified (Oswald, 1995), and Soeder (1986) had noted the HRAP, applied to waste water treatment, as offering the greatest potential of all microalgal biotechnologies to be exploited as a multi-purpose system. A striking hiatus was evident, however, between the optimistic promise of algal biotechnology, and actual delivery, in terms of fully operational systems.

It was against the background of these developments that the WRC study commenced in 1990 as a preliminary investigation of the potential available, in this broadly emerging area of biotechnology, to deal with local issues of sustainability in salinity and sanitation. The specific objective of the initial project K5/410 'A biotechnological approach to the removal of organics from saline effluents', was to identify potential research targets and to evaluate the feasibility and need for a longer-term research strategy in meeting these problems. In addition to providing potential technological solutions to the salinity and sanitation problem, the following studies provided the opportunity to evaluate an 'integrated wastewater resource management' strategy as a model system in which ultimate targets of 'closed system' sustainability might be progressed. Underpinning this development was the principle of beneficiation, and an understanding that sustainable environmental practice in the long-term will come to depend ultimately on meeting market forces rather than relying on regulatory enforcement alone.

It was noted at the outset that in the technology-push stage in which environmental biotechnology has tended to engage with sustainability issues, progress would likely be incremental and probably include a high rate of attrition. However, as the sustainability project matures, and as these technologies develop, aspects of current progress would be picked up and incorporated as unit operations in a wider range of process developments. While the studies reported here have in some way contributed to this process in industrial scale-up and technology transfer initiatives, an underlying objective has also been the training of the associated human resources required to progress initiatives in this broad area.

9.1 OUTPUTS

In terms of these objectives the study has developed, or demonstrated an extension of, bioprocess applications in a number of wastewater treatment areas relating to the linkage of the salinity and sanitation systems. In the course of the study the following has been shown:

- Saline and sulphate-saline wastewaters may be feasibly treated in algal ponding systems and, with the removal of organic and metal pollutants, may be rendered safe for segregation from the public water system in saline wastewater impoundments. This will provide increased safety in saline wildlife refuge areas and recreational wetlands, aspects of which inevitably develop around these sites;
- The IAPS concept provides a useful base as a 'core technology' for bioprocess innovation in both saline and sanitation wastewater treatment applications. These include small community sanitation, where technological sustainability may be achieved in terms of low-cost construction and operation, a low operational skills requirement, and 'upgradeability' to include the treatment of industrial wastewaters as communities develop economically. Industrial applications of IAPS wastewater treatment demonstrated in these studies include tannery, abattoir, winery and distillery and acid mine drainage wastewaters;
- Nutrient values present in both saline and sanitation wastewaters may be recovered in IAPS in the form of value-added algal bio-products, and their return to both the economy, and the biological environment, provides enabling technologies for establishing 'integrated wastewater resource management' beneficiation objectives in the management of these wastes;
- The co-disposal of sulphate-saline and domestic wastewaters as linked utility operations provides not only for novel processing in organic waste disposal but, importantly, also for the long-term treatment of AMD following mine closure, an issue directly affecting the sustainability of the mining environment. The Rhodes BioSURE Process® has achieved the linkage of these objectives;
- In addition to the biosulphidogenic disposal of sewage sludges, a range of other complex organic carbon sources, including lignocellulosic wastes, may be mobilised biosulphidogenically in the BioSURE Process® to produce electron donor sources for AMD treatment, and also potentially for a range of other biological work such as nutrient removal;
- Algal production of high-value biomass and speciality fine chemical products may feasibly be incorporated with the treatment and disposal of saline and sanitation wastewaters and, in this way, provide an opportunity for their sustainable beneficiation and cost-effective management;
- In addition to a range of other possible by-products, treated water may provide the most durable product of the beneficiation process. Where a cycle of productive use is allowed following wastewater treatment, and prior to its return to the public water system, this may present the strongest incentive to the private operator to undertake

the beneficiation of these wastes. The Eskom Sustainable Development Project in Integrated Wastewater Resource Management described below provides an example of attempts to link environmental sustainability and sustainable development in this way.

In the course of the WRC studies summarised in this report the following tangible outputs have been produced:

- Publication of 12 separate WRC project reports. The details of these reports are listed in Appendix 1;
- Student training has included 2 Post-Doctoral Fellows, 11 PhD and 14 MSc theses. These are noted in Appendix 2;
- Publication of the results of these studies is ongoing but currently includes 17 patents, 24 journal papers, and 8 articles of general scientific interest. Publication in conference proceedings includes 5 plenary and keynote papers, 24 international and 73 local conference presentations. Publication outputs are reported in Appendix 2;
- A number of industrial technology transfer exercises have been undertaken, involving the products of these studies, and are noted in Appendix 3;
- Research spin-off developments which have resulted in associated follow-up research projects have been noted in Appendix 4.

9.2 FOLLOW-UP DEVELOPMENTS

Beneficiation in the saline and sanitation wastewater systems, and especially as related to mining wastewaters and the mine closure problem, may provide primary technology and resource inputs to quite complex 'integrated wastewater resource management' production programmes. The Eskom Sustainable Development Project described below presents a current example where both treated water and a range of biological production potential has been investigated. This project provided an opportunity to evaluate the application of the wastewater beneficiation strategies which had been investigated in the WRC study.

9.2.1 The Eskom Sustainable Development Project

The mine closure issue presents problems in environmental and social development which seriously constrain the mining industry in South Africa. Acidic and sulphate-saline wastewaters, often including substantial heavy metal contamination, are likely to decant from South African coal and gold mines for many decades, and possibly centuries, following cessation of mining operations (Younger, *et al.*, 1997). While official mine closure certification depends on provision being made for the treatment of these flows, enormous social problems may also follow the closure process. Despite severance gratuities and retraining initiatives, large populations of dislocated, and now indigent, people may remain around a workplace and in a social environment that has evolved over a period of many decades. The linkage of minewater treatment and the utility operator presents a sustainable option for closure and ultimate walk-away by the mining company. Attempts to link a long-term and sustainable wastewater treatment operation with sustainable social development, provides another option to deal with this problem, and this forms the subject of an Eskom project in 'integrated wastewater resource management' in which preliminary studies commenced in 2001.

Although this type of approach is now only in initial stages of development, an account of the Eskom programme is presented as a conclusion to this report, not only due to its incorporation of aspects of the WRC study, but in that it also offers a model wherein the development of the grand plan 'closed system' approach can be critically examined and evaluated. Clearly the future of 'closed system' sustainability will depend on organisations with the incentives, the resources and the capacity to explore these options.

The New Denmark Colliery is one of a number of coal mines supplying electricity generation at the Tutuka Power Station in the Mpumalanga Region. In addition to currently experienced water problems, the mine is expected to decant potentially large volumes of poor quality sulphate and chloride saline wastewaters which will discharge to the Leeuspruit River in the upper regions of the already water stressed Vaal River catchment. A well-established and large community infrastructure, currently providing labour to the coal mining and power generation enterprise in the area, is also under the threat of disintegration on mine closure. The Sustainable Development Project in 'integrated wastewater resource management' is designed to link long-term AMD water treatment, and the recovery of treated water, with a community rehabilitation initiative providing a sustainable employment base in the region.

Figure 9.1 shows the integrated unit operations involved in the Eskom Sustainable Development Project. In this proposal the Rhodes BioSURE Process® forms the pretreatment operation in which sulphate and calcium salinity is reduced, heavy metals precipitated and the wastewaters neutralised prior to further down-stream utilisation. Water and sulphur will form the principal products of this operation. Part of the treated and demineralised water stream would be returned to mining and power generation while these are still in operation, with reverse osmosis removing the residual chloride salinity. The saline reject streams would pass to saline wastewater impoundment where both *Spirulina* and *Dunaliella* production would be engineered in solar evaporation ponding cascades. In addition to a range of biological products and finally salt production, the algal biomass production may be used in speciality ration formulation for the associated aquaculture production operations.

A range of labour- and capital-intensive horticulture and aquaculture enterprises have been investigated in which the residual wastewater stream may be utilised. These include small stock production based on intensive cultivation of Atriplex, the 'old man saltbush', hydroponic vegetable production and also salmonoid and tilapia fish for the nearby Gauteng market.

It is envisaged that the New Denmark system will handle around 20 $ML.day^{-1}$ contaminated minewater, and that both maize production wastes from the surrounding maize farming industry in Mpumalanga, and other organic materials generated across the enterprise, will provide the electron donor and carbon source necessary for the BioSURE® operation.

The EBG was involved in a preliminary study undertaken in 2001 to evaluate the feasibility of the BioSURE® component of the system. Salt reduction in Atriplex hydroponic systems, and vegetable and aquaculture production were also investigated at this time.

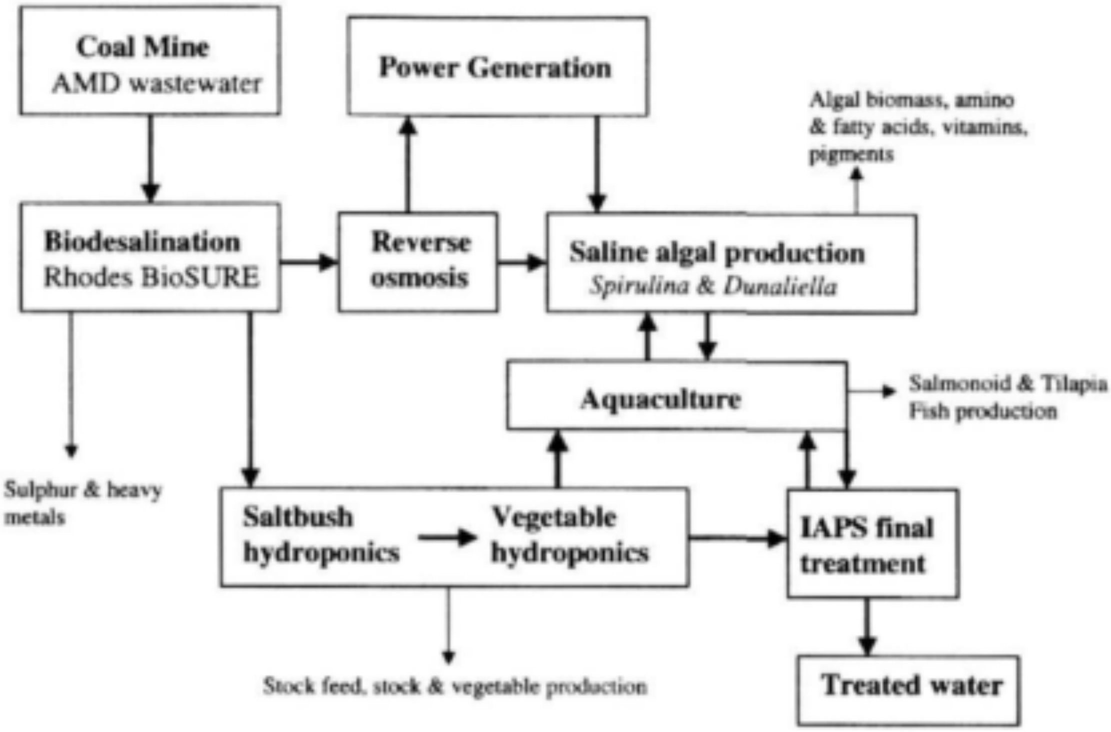


Figure 9.1. The Eskom Sustainable Development Project in 'integrated wastewater resource management' based on the biodesalination and treatment of coal mine wastewaters using the Rhodes BioSURE Process® as the initial process step. Following biodesalination the partly demineralised stream containing residual chloride salinity passes to reverse osmosis and back to power generation. The chloride saline reject stream passes to meso- and hyper-saline algal production systems. Residual partly treated water may be used in aquaculture, salt bush, stock rearing and intensive horticulture production operations. Treated water may pass via an IAPS polishing step to discharge in the public water system.

Although such systems are still in very early stages of development worldwide, programmes targeting 'closed system' production objectives may contribute to sustainable development targets. In addition to addressing the needs of the bio-physical environment they can also contribute to sustainable development objectives, important issues of policy in South Africa.

9.3 A FUTURE FOR THE CLOSED SYSTEM ?

Sustainability, as a concept reconciling the apparently conflicting trajectories of human development and the needs of the bio-physical environment, has emerged as a powerful source of innovation in the global environmental project. Achieving the goals of sustainability, as Jansen (1997) has observed, involves nothing less than a fundamental renewal of the whole means by which human needs are fulfilled. It is in this regard that the growth of the environment industry, over the past 15 – 20 years, has formed a crucial component of what Roobeek (1995) has called a quantum shift in the World economy from 'Fordist' to post-industrial paradigms.

It is in the context of sustainability objectives that environmental biotechnology has emerged as an interface between fundamental biology and engineering application, and providing a potential source of innovation in the pursuit of 'integrated wastewater resource management' approaches to production and technological activity. This general focus relates in particular to the development of enabling technologies required to facilitate an increasingly effective separation of the human and bio-physical environments as 'closed systems'.

The targets of sustainability have generally proved easier to identify than achieve, and delivery apparently remains dependent ultimately on technological capacity, and on-going innovation, in one form or another. Suzuki (2000) has noted the non-trivial nature of establishing 'closed systems' within the already fully optimised industrial economy which, together with a range of other factors, has led to a technology-push approach in the initiation of sustainable technology research. In this regard progress is also likely to be incremental, with small steps achieved in a range of different areas, being combined eclectically to achieve increasing closure of the 'integrated resource management' operation. While the implementation of grand plan 'closed system' foci of production may seem to lie in the future, the emergence of systematic approaches to their design are already emerging.

In terms of technology life-cycle these factors imply both a high-risk research approach, and an anticipated high attrition rate in obsolescence as developments are rapidly superceded. Issues of obsolescence lie at the core of the technology R&D enterprise in any event, and development towards a 'closed system' sustainability is likely to be a highly dynamic process involving innovation and replacement across wide areas of environmental activity. However, research significantly also provides the structure in which the human resource is generated. Possibly more important than the actual technological tools emerging, and the length of time these may remain in current use, is the development of the people and the skills needed to address the problems of the future as these arise. Human capital, rather than natural capital, may prove to be one of the few truly sustainable resources available to the human project over the long term.

Whether the technology-push approach to beneficiation developments will successfully provide component units in larger grand scheme 'closed system' and 'integrated waste resource management' programmes, or possibly merely add useful incremental advances on the existing technology base, will be determined equally by a process of technology development and market evaluation. It seems that no amount of structured socio-economic planning can circumvent this reality.

Drummond and Marsden (1999) have commented adversely on approaches to sustainable development which require the ability to regulate, throughout the whole gamut of human activity, in a detailed and co-ordinated manner. "It seems to be highly improbable that sustainable development can be effectively promoted solely through use of concrete forms of regulation which address specific problems, be they prohibitive legislation, fiscal measures, or whatever. The effective articulation and operationalisation of such an approach is almost certainly beyond the scope of human agency. It would require the management of what is in practice probably unmanageable." Hayek (1988) has argued that contemporary societies and economies are now so complex that adequate knowledge for such large-scale planning cannot possibly exist.

It seems, therefore, that one route to sustainability involves the linkage of fundamental and applied research and the related testing of innovative potential. A technology-push approach, which now characterises much activity in environmental biotechnology, gives rise to a potentially rich crop of technological options in 'closed system' sustainability. This process, however, may or may not finally contribute to the targeted renewal of the means of production. It will find its ultimate validation or otherwise, not in carefully managed social programmes or the artificially structured grand plan, but in the end in the subjection of these contributions to the rigorous assessment of the market place. The studies reported here have been undertaken with this in mind, and as one among many initial contributions to this process.

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11 APPENDICES

APPENDIX 1.

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.
Part1: 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 under which the various investigations of the programme were undertaken, together with the appropriate reports in which the study results have been detailed:

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.

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. Part 1: 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. Part 1: 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 Reciprocating 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 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 4: System Performance and Tertiary Treatment 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.

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.

APPENDIX 2

RESEARCH PRODUCTS

The results of the WRC study, and the research products which have been generated, have been the subject of detailed report in student theses, journal articles, patents and other publications, in addition to the project reports identified in Appendix 1.

2.1. STUDENTS TRAINED

2.1.1 Post-Doctoral Fellows

Dr. O. Shipin (1992-1993) Rate Determinants in Hyper-saline Anaerobic Digestion.

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

2.1.2 PhD Students

T. Phillips (1994) Stress manipulation in *Dunaliella salina* and dual – stage β-carotene production.

M. Logie (1995) Physiological signal transduction from the photosynthetic apparatus in the green alga *D.salina*.

L. Phillips (1995) Constituent processes contributing to stress induced β-carotene accumulation in *D.salina*.

K. Dunn (1998) The biotechnology of high rate algal ponding systems in the treatment of saline tannery wastewaters.

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

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

D. Sanyahumbi (current) The manipulation of immobilised sulphate reducing bacterial systems.

L. Dekker (current) Integrated algal ponding systems and the treatment of wine processing wastewaters.

H. Roman (current) Digestion of lignocellulose in sulphate reducing environments.

C. Ehlers (current) The degradation of aromatic compounds in sulphate reducing environments.

A. Clarke (current) The molecular microbial ecology of lignocellulose degradation in biosulphidogenic environments.

2.1.3 MSc Students

R.K. Laubscher (1992) The culture of *Dunaliella salina* and the production of β-carotene in tannery effluents.

B. Maart (1993) The biotechnology of effluent-grown Spirulina and application in aquaculture nutrition. (Degree awarded with distinction.)

D. Glaum (1994) A process for the detanning of chrome leather wastes using tannery effluents.

R. Emmett (1996) Glycerol production by *Dunaliella* in saline wastewater treatment.

P. Molepane (1999) Sulphate reduction in complex organic substrates.

P. Masemola (2000) The nature and control of organic compounds in soda ash evaporite production.

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

C. Corbett (2001) Development of the Rhodes BioSURE Process® in the treatment of acid mine drainage wastewaters.

S. Clark (2002) The independent high rate algal pond as a unit operation in tertiary wastewater treatment.

N. Rein (2002) Biological sulphide oxidation in heterotrophic environments.

G. Chauke (2002) The molecular microbial ecology of sulphate reduction in the Rhodes BioSURE Process®.

M. Madikane (2002) Biosulphidogenic hydrolysis of lignin and lignin model compounds.

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

M. Bowker (2002) The biology and molecular ecology of floating sulphur biofilms.

2.2. PUBLICATIONS

2.2.1 Patents

1. Rose,P.D. 1992. Treatment of saline effluent.
   RSA 91/5069 (final)
   Namibia F0791 (final)

2. Rose,P.D., Cowan,A.K. 1992. A process for the production of useful products from saline media.
   RSA 91/5070 (final)
   Australia 19345/92 (final)
   Namibia F07913 (final)
   USA 906536 (final)
   EPO 92306077.4 (final)
   Israel 102357 (final)

3. Rose,P.D., Cowan,A.K. 1992. A process for the treatment of saline effluents.
   RSA 92/4865 (final)
   Australia 19344/92 (final)
   Namibia F07911 (final)
   USA 906535 (final)
   EPO 92306078.4 (final)

4. Rose,P.D. Cowan,A.K. 1992. Treatment of saline media with *Spirulina*.
   RSA 92/4159 (final)

5. Rose,P.D., Glaum,D., Rowswell,R.A. 1992. A process for the removal of chromium from tanned leather.
   RSA VO 8584 (final)

6. Rose,P.D., Phillips,T.D., Sanderson,R. 1993. A process for the membrane-based extraction of β-carotene.
   RSA 93/0953 (final)

7. Russell, A.E., Tandt, H., Kohl, R.C. and Rose, P.D. 1995. Preservation of animal hides and skins.
   RSA 95/0559 (final)

8. Rose P.D., Boshoff, G.A., Hart, O.O., Barnard, J.P. 1997. The double deck trench reactor.
RSA 97/4165 (final)
Australia 711069 (final)

9. Rose P.D., Duncan, J.R., van Hille, R.P., Boshoff, G.A. 1998. Alkalinity and biorefining.
RSA 98/3204 (final).

10. Rose,P.D., and Hart, O.O. 1988. Treatment of Water-modification.
RSA 98/9429 (final)

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

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

13. 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.

14. Leukes,W., Jacobs, E., Rose, P., Burton., and Sanderson, R. 1999. Methods for producing secondary metabolites.
US 5945002.

15. 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.

16. Rose, P.D. and Hart, O.O. 2000. Treatment of water ontaining carbonaceous solids.
PCT (Patent Cooperation Treaty) WO 00/21891. (133 designated states).

17. Pulles, W. and Rose, P.D. 2002. Passive water treatment.
RSA 2001/3493.

2.2.2 Papers

1. Cowan, A.K. and Rose, P.D. 1991. Abscisic acid metabolism in salt stressed cells of *Dunaliella salina*; a possible interrelationship with β-carotene accumulation. Plant Physiology, 97: 798-803.

2. Cowan, A.K. and Rose, P.D. 1991. Is there a role for abscisic acid in the response of the green alga *Dunaliella salina* var. Bardawil to salinity stress? Abstract – Plant Physiology, May 1991.

3. Rose,P.D.,Maart,B.A.,Phillips,T.D.,Tucker,S.L.,Cowan,A.K. and Rowswell,R.A. 1992. Cross-flow ultrafiltration used in algal high rate oxidation pond treatment of saline organic effluents with the recovery of products of value. Water Science and Technology, 25: 319- 327.

4. Cowan,A.K., Rose,P.D. and Horne,L.G. 1992. *Dunaliella salina*: A model system for studying the response of plant cells to stress. Journal of Experimental Botany, 43:1535-1547.

5. Brady, D., Letebele, B., Duncan, J.R. and Rose, P.D. 1994. Bioaccumulation of metals by Scenedesmus, Selenastrum and Chlorella algae. Water S.A., 20: 213-218.

6. Brady, D. Rose, P.D and Duncan, J.R. 1994. The use of hollow fibre cross-flow microfiltration in bioaccumulation and continuous removal of heavy metals from solution by Saccharomyces cerevisiae. Biotechnology and Bioengineering, 44:1362-1366.

7. Cowan, A.K., Logie, M.R.R., Rose, P.D. and Phillips, L.G. 1995. Stress induction of zeaxanthin in the β-carotene-accumulating alga *Dunaliella salina* Teod. Journal of Plant Physiology, 146:547-553.

8. Phillips. L., Cowan, A.K., Logie, M.R.R. and Rose, P.D. 1995. Operation of the xanthophyll cycle in non-stressed and stressed cells of *D.salina*. Journal of Plant Physiology, 146:554-562.

9. Rose, P.D., Maart, B.A., Dunn, K.M., Rowswell, R.A. and Britz, P. 1996. High Rate Oxidation Ponding for the treatment of Tannery Effluents. Water Science and Technology 33:219-227.

10. Rose, P.D. and Hart, O.O. 1996. The saline water algal high rate oxidation pond- capacity building in the developing world. Abstract – Journal of Applied Phycology, 8(4-6):456.

11. Phillips, T.D. and Rose, P.D. 1996. Partitioning of globular and membrane bound β-carotene in response to light stress. Abstract – Journal of Applied Phycology, 8(4-6):454.

12. Phillips, L.G., Cowan, A.K. and Rose, P.D. 1996. Xanthophyll cycle operation in *Dunaliella salina*: a possible correlation with enhanced β-carotene accumulation. Abstract – Journal of Applied Phycology, 8(4-6):453.

13. Boshoff, G., Duncan, J. and Rose, P.D. 1996. An algal-bacterial integrated ponding system for the treatment of acid drainage waters. Abstract – Journal of Applied Phycology, 8(4-6):442

14. 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.

15. Shipin, O.V., Meiring, P.G.J. and Rose, P.D. 1998. Petro system: a low-technology approach to the removal of wastewater organics. Water SA, 24: 347-354.

16. Shipin, O.V., Rose, P.D. and Meiring, P.G.J. 1999. Microbial processes underlying the PETRO concept. (Trickling Filter Variant). Water Research, 33:(7)1645-1651.

17. 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.

18. 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 BioSURE Process® for Sewage Sludge Solubilisation. Chemical Technology, March/April, 2001.

19. 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.

20. C.G. Whiteley, P. Heron, B.Pletschke, P.D. Rose, S. Tshivhunge, F.P. van Jaarsveld and K.Whittington-Jones. 2002. The Enzymology of Sludge Solubilisation Utilising Sulphate Reducing Systems. Properties of Proteases and Phosphatases. Enz., Microbiol. Tech. (Accepted, 2002).

21. C.G. Whiteley, P.Rose, B.Pletschke and X.Melamane. 2002. Environmental enzymology: Enzymology of accelerated sludge solubilisation: Properties of Lipases. Water Research. (Accepted, 2002).

22. C.G. Whiteley, P.Rose, and B.Pletschke. 2002. Environmental enzymology: Enzymology of accelerated sludge solubilisation: Role of ATP Sulphurylases. Enz., Microbiol. Tech. (Accepted, 2002).

23. C.Whiteley, B.Pletschke, P. Rose and N.Ngesi. 2002. Specific Sulphur Metabolites Stimulate β-Glucosidase Activity in an Anaerobic Sulphidogenic Bioreactor. Biotech. Letts. (Accepted, 2002).

24. Ristow, N.E., Whittington-Jones, K., Corbett, C., Rose, P.D. and Hansford, G.S. 2002. Modelling of a recycling sludge bed reactor using AQUASIM. Water SA, 28:(1) 111-120.

2.2.3 General Articles

1. Meiring, P.G.J., Rose, P.D. and Shipin, O.V. 1994. Algal aid puts a sparkle on effluent. Water Quality International, 2:30-32

2. Gibbs, S. 1995. Sewage Treatment Plants: Algae offer a cheaper way to clean up wastewater. Scientific American, 273:27.

3. Rose, P.D., Maart, B.A., Dunn, K.M., Rowswell, R.A. and Brits, P. 1995. Ponding presents Potential. Leather 83-90, September 1995.

4. Burnett, M. Training programmes for the leather industry. FRD Scientech '96.

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APPENDIX 3

TECHNOLOGY TRANSFER ACTIVITIES

Notwithstanding the exploratory objectives of the study, and focus on the investigation of potential available in an environmental biotechnology approach to salinity and sanitation sustainability, the brief included a specific requirement to pursue 'technology-push' opportunities where these arose. While aspects of technology development resulting from the study have been described above, it was also a specific component of the WRC brief that these should be the subject of technology transfer initiatives.

A number of activities were undertaken during the course of the programme to make known findings and results, and to assist in technology diffusion and technology transfer to potential users. These included official opening functions, technical visits and technical tours to the sites involved.

3.1 OFFICIAL OPENING IAPS DEMONSTRATION AND RESEARCH PLANT

The IAPS demonstration and research plant constructed at the Environmental Biotechnology Experimental Field Station in Grahamstown was a joint project involving the WRC, Grahamstown Municipality and Rhodes University. It was designed to serve the dual function of a technology demonstration plant and a research facility for algal biotechnology and environmental biotechnology studies. The plant was officially opened by the Hon. Minister of Water Affairs and Forestry, Prof Kader Asmal, in April, 1997 (Figure A 3.1). The event was attended by some 300 local people, engineers, scientists and senior government officials.

Figure A3.1. Hon. Minister of Water Affairs and Forestry, Prof Kader Asmal handing over the keys of the plant to the Mayor of Grahamstown Cnlr. Mpahlwa. Background from left to right: Dr D Woods, Vice Chancellor Rhodes University; Dr O Hart and Prof P Rose, Rhodes University EBG.

3.2 OFFICIAL OPENING OF THE MOSSOP-WESTERN LEATHERS Co. TANNERY IAPS

Following research described in Chapter 8 relating to the performance and operation of the tannery WSP in Wellington, the Mossop Western Leathers Co. undertook the full-scale implementation of the IAPS development. This involved construction of the *Spirulina*-HRAP and incorporating retrofitted ponding units into the established WSP system.

The industrial-scale IAPS plant treating tannery wastewaters was officially opened by the Hon. Minister of Water Affairs and Forestry, Prof Kader Asmal, on 28 November, 1997 (Figure A 3.2). The event was attended by about 250 local people, engineers, scientists and senior government officials. Harvesting of the *Spirulina* biomass has been commercialised and a biomass sales enterprise has been initiated by former EBG student Len Dekker (Figure A 3.2).

Figure A3.2. Above. Minister of Water Affairs and Forestry, Professor Kader Asmal, opening the Tannery IAPS Plant. From the left Mr Tony Mossop, MD Mossop Western Leathers Co., and Professor Colin Johnson, Chairman of the Water Research Commission. Below. Former EBG student Len Dekker and assistant harvesting *Spirulina* biomass on a Sweco screen, an operation in the commercial production of *Spirulina* biomass.

3.3 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® took place largely 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 Environmental Biotechnology Experimental Field Station in Grahamstown to facilitate both fundamental and process scale-up/scale-down investigation methodologies.

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 (Figure A3.3). The event was attended by around 150 people including conference delegates from academia, industry and government.

Figure A3.3. 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.

3.4 THE GROOTVLEI TECHNOLOGY EVALUATION EXERCISE

Circumstances relating to the dewatering of the Grootvlei Gold Mine, and the associated damage to the Blesbokspruit and the Marievale Ramsar site have been described in Chapter 7. A component of the decision by Government to allow resumption of pumping activities was that a competitive technology evaluation exercise be undertaken to determine the long-term course of action by which mine drainage wastewaters would be treated. Some 14 technology bids were received and in the end four of these resulted in on-site evaluation studies.

The Rhodes University EBG was requested to participate in this exercise and the BioSURE Process® pilot plant was constructed on-site at No. 3 Shaft, Grootvlei Mine, early in 1998 (Figure A3.4). The results of this study have been reported in Chapter 7.

Figure A3.4. The Rhodes BioSURE Process® pilot plant constructed in Grahamstown by Grahamstown Engineering Co., transported to Grootvlei Gold Mine, Gauteng, and erected on site.

3.5 TECHNICAL TOUR

A technical tour of inspection of developments in the WRC study relating to IAPS Technology in South Africa was undertaken 24 – 26 January, 1996 (Figure A3.5). Members of the Technical Committee included: Prof C.T. Johnson (Chairman WRC); Mr P.E. Odendaal (Executive Director WRC); Mr D.S. van der Merwe (Deputy Director WRC); Mr Z. Ngcakani (Research Manager WRC); Mr J.R. Muller (Abakor); Dr A. Jarvis (Sasol Co.); Dr O.O. Hart (Rhodes University); Prof P.D. Rose (Rhodes University).

Sites visited included:

1. SASOL β-carotene production technical scale plant in Upington.
2. WRC/Mossop Western Leathers commercial scale IAPS plant in Wellington.
3. WRC demonstration plant IAPS sewage treatment in Grahamstown.
4. WRC/Abakor demonstration IAPS plant at Cato Ridge Abattoir.
5. De Beers pilot plant for treatment of diamond wastes at De Beers Diamond Research Laboratory, Johannesburg.

Figure A 3.5. Technical tour party which undertook the inspection of WRC AIPS project installations. From left to right Prof P.D. Rose (Rhodes University); Mr D.S. van der Merwe (Deputy Director WRC); Mr Z. Ngcakani (Research Manager WRC); Prof C.T. Johnson (Chairman WRC); Mr J.R. Muller (Abakor); (Pilot); Dr O.O. Hart (Rhodes University); Dr A. Jarvis (Sasol Co.); Mr P.E. Odendaal (Executive Director WRC).

3.6 SITE VISITS

1. Technical tours to the IAPS Demonstration and Research Plant and Environmental Biotechnology Experimental Field Station at the Grahamstown Disposal Works, were held during the 1996 Port Elizabeth WISA Conference and the BIOY2K Mine Water Conference, January 2000 (Figure A 3.6). Approximately 150 visitors, including engineers, scientists, local government and DWAF officials, attended each function.

2. The Wellington IAPS has been visited by hundreds of people since its official opening, and the full-scale plant has played an important role in the decision to proceed with certain of the process applications described below.

3. The IAPS Demonstration and Research Plant has been visited by nearly 3000 people since its opening, including scientists, engineers, municipal officials, students, scholars and the general public. It has attracted particular attention at the Grahamstown Scifest, and is regularly used for teaching students in environmental biotechnology, industrial microbiology, applied biochemistry and environmental economics.

Figure A 3.6. Technical visit to the Environmental Biotechnology Field Station during the Mine Water Conference, January 2000.

APPENDIX 4

RESEARCH SPIN-OFF DEVELOPMENTS

The studies undertaken in this programme have touched on a number of issues which, while in their initial phase were closely related to the WRC projects, have now developed a separate life of their own. While these have been followed up as separate initiatives, largely under the leadership of colleagues and collaborators, it is important to note the linkages to the study described here in defining the circle of influence established by the WRC investment in the IAPS as a 'core technology' activity.

4.1 MEMBRANE BIOREACTORS

Studies undertaken in Project K5/495, using membranes for cell harvesting and the separation and recovery of β-carotene in the hot oil extraction method, led to a WRC programme which undertook the development of membrane bioreactor applications. This developed into a joint study together with Prof Ron Sanderson and Dr Ed Jacobs of the Polymer Institute, Stellenbosch University, and Drs Stephanie Burton and Winston Leukes and the author, Rhodes University. Both novel membrane and membrane bioreactor developments have emerged from this initiative and the research involves a number of follow-up projects including an ESKOM TESP programme, and the participation of Peninsula Technikon, Cape Technikon, and the ML Sultan Technikon in a multi-disciplinary R&D initiative.

4.2 METALS AND BIOHYDROMETALLURGY

The early studies in metal removal in algal ponding systems also involved investigation of membrane-based approaches to heavy metal removal, and explored the role of bioadsorption and bioaccumulation by microbial biomass. The role of algal ponding systems was shown to provide the basis for process development in free-standing HRAP systems. These studies were undertaken in collaboration with Prof John Duncan and this now forms an independent WRC programme in biohydrometallurgy at Rhodes University.

4.3 UCT DEPARTMENTS OF CHEMICAL AND CIVIL ENGINEERING

Following the biotechnology studies and bioprocess developments, relating to the Rhodes BioSURE® Process reported in Chapter 7, a number of collaborative studies commenced with the UCT Departments of Chemical and Civil Engineering, to undertake the modelling of particular aspects of the system. Both computer models of the process and descriptive accounts of the aqueous chemistry of these systems have resulted, and these initiatives have developed into separate WRC projects.

4.4 THE ENZYMOLOGY OF SLUDGE HYDROLYSIS

Preliminary studies had shown a relationship between the physico-chemical conditions prevailing in the RSBR and enzymatic activity resulting in the sludge hydrolysis and solubilisation patterns observed. These studies have become the focus of a separate programme in environmental enzymology under the leadership of Prof Chris Whiteley.

4.5 PASSIVE SYSTEMS AND THE INNOVATION FUND PROJECT

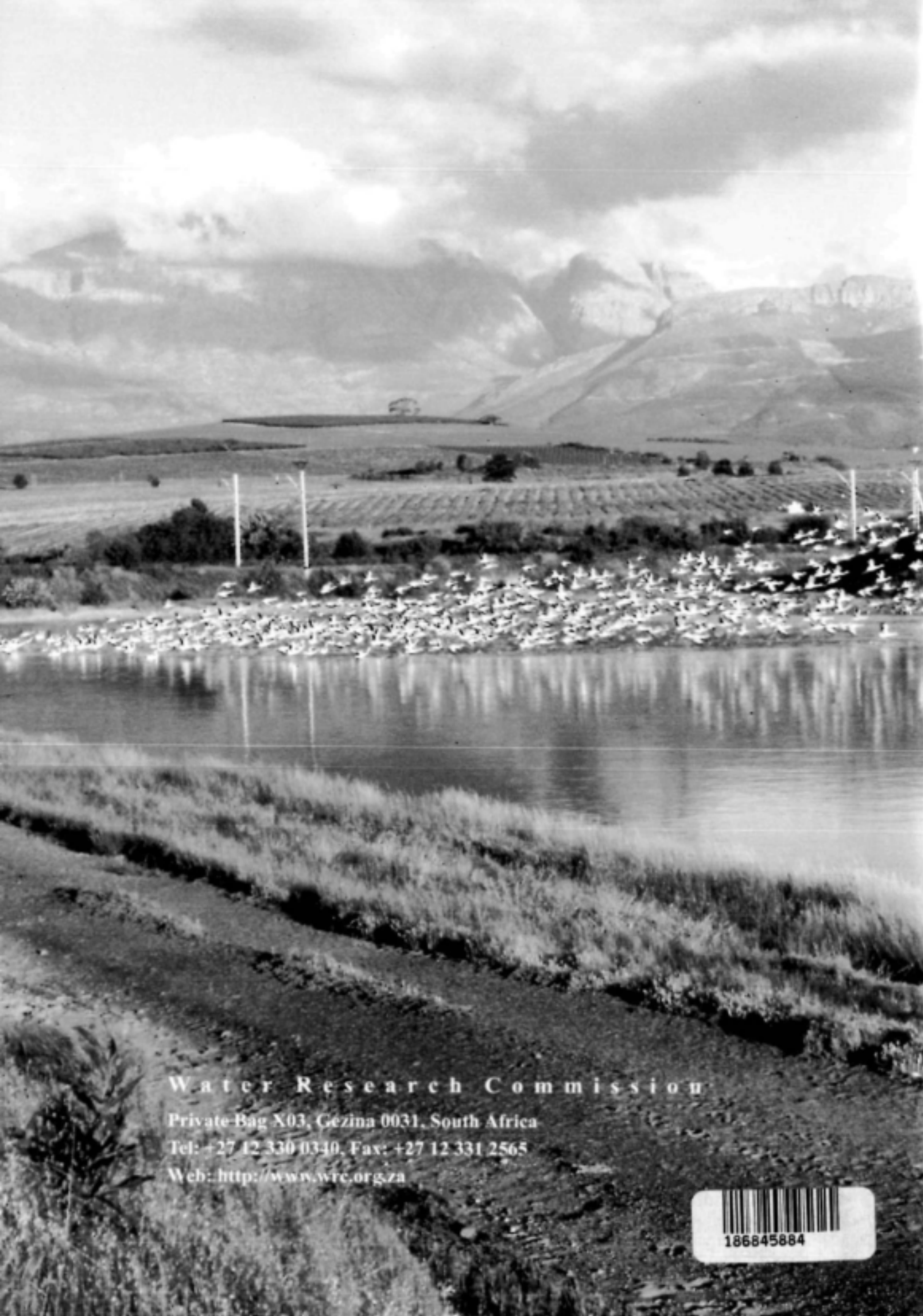
Passive treatment systems for the remediation of mine drainage wastewaters have been under investigation by William Pulles of PHD Co. The Rhodes EBG was invited to participate in the Department of Arts Culture Science and Technology (DACST) Innovation Fund award in which the commercialisation of sulphate removing passive treatment systems was to be investigated. Current research is investigating the application of the 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.

4.6 ESKOM SUSTAINABLE DEVELOPMENT PROJECT

Eskom have undertaken the application of various aspects of the WRC study in a programme to establish a comprehensive 'integrated resource management' approach to coal mining wastewaters. In addition to water treatment the project aims to develop aspects of the value recovery and beneficiation findings which have developed in the WRC study, including job creation and community rehabilitation initiatives in preparation for mine closure. This undertaking involves the use of the Rhodes BioSURE® Process as a pretreatment to RO membrane desalination, effecting the removal of metals, sulphate, calcium and other scaling salts, and the return of the treated water to mining and power generation requirements. The saline reject streams would pass to *Spirulina* and *Dunaliella* solar evaporation ponding cascades where biomass and fine biochemical production would be used as a component of downstream beneficiation operations. The ESKOM project would ultimately handle a minewater stream of 20 $Ml.day^{-1}$, and provides an opportunity for the large-scale evaluation of the 'integrated resource management' objectives which formed one of the major motivations for the WRC programme.

4.7 NUTRIENT REMOVAL IN DIAMOND SORTHOUSE WASTEWATERS

De Beers Co. have undertaken the evaluation of the I-HRAP as a free-standing unit operation for N removal from diamond sorthouse wastewaters. A 100 m^2 HRAP pilot plant was constructed at the De Beers research laboratories at City Deep, Johannesburg.



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