An Assessment of the Key Factors that Influence the Environmental Sustainability of a Large Inland Industrial Complex

Volume II:

Inventory of Inland Salt Production and Key Issues for Integrated Cleaner Production for Waste Salt Management at the Highveld Mining and Industrial Complex

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WATER RESEARCH COMMISSION

TT 545/12

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by

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Water Research Commission
Private Bag X03
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orders@wrc.org.za or download from www.wrc.org.za

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Volume I: Inception report **(TT 544/12)**
Volume II: Inventory of inland salt production and key issues for integrated cleaner production for waste salt management at the Highveld mining and industrial complex **(TT 545/12)**
Volume III: Development and assessment of technological interventions for cleaner production at the scale of the complex **(TT 546/12)**
Volume IV: Governance assessment **(TT 547/12)**
Volume V: Linking technologies to governance **(TT 548/12)**

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Prof Harro von Blottnitz	University of Cape Town
Mr Chris Brouckaert	University of KwaZulu-Natal
Ms Cornelia Ras	University of Cape Town (Student)
Ms Floor Hooijman	Technical University of Delft (Student)
Ms Thandeka Nene	University of KwaZulu-Natal (Student)
Ms Nirvana Reddy	University of KwaZulu-Natal (Student)
Ms Devi Naicker	University of KwaZulu-Natal (Student)
Ms Joshna Kampallal	University of KwaZulu-Natal (Student)
Mr Glen Jansen	University of Cape Town (Student)
Ms Dineo Kadi	Cape Peninsula University of Technology (Student)

EXECUTIVE SUMMARY

BACKGROUND

This study is Volume II of the WRC project to identify and assess the key factors for the environmental sustainability of a large inland industrial complex associated with mining.
Other components of the project are:

- The inception report (Volume I) outlining the problem definition and ranking of all the potential complexes in South Africa that could qualify as a complex with industrial cooperation. The Highveld Industrial and Mining Complex received the highest priority for a complex that could provide data on the research objectives. These included environmental sustainability, combination of mining industry, and processing or manufacturing industry and the storage of salts and saline waters.
- A governance survey (Volume III) to identify the needs and perceptions of the main stakeholders in the industrial complex.
- An evaluation of integrated cleaner production technology options which was carried out in parallel with this study (Volume IV).
- An integration of the governance survey with the findings of the inventory study (Volume V).

Components included in this report are

- Industry specific inventories for each of the main salt and water consuming and producing processes with the objective of identifying and quantifying the sources and destinations of the salt and water flows inside the boundaries of each set of mine operations, and each set of energy transforming operations of coal to electricity, and gas and coal to liquid fuels and other chemical products.
- Catchment specific flow inventories and long term trends for flow periods over 34 years. Salinity is measured using the DWA measurement system, i.e. for aqueous ions measured by (pH, Na^+, Cl^-, K^+, F^-, Mg^{2+}, Ca^{2+}, SO_4^{2-}, and total alkalinity for HCO_3^-). Flow and water quality sampling points in the Waterval and Leeuspruit Rivers are below all the industries account for all permitted point source discharges
- A comparison of industrial and natural flows of salts provides a method to identify the industrial contribution to current surface water flows and an indication of long term trends. Industrial flows have higher proportions of Na^+, Cl^-, and SO_4^{2-}, and a variable pH due to underground dissolution of carbonates and acidification with sulphides initially and heavy metal redox reaction subsequently. Higher amounts of measured stream flows than measured discharges provide a measure of non-point discharges. The largest salt storage sites are candidates for non-point discharge because most of the storage sites are not lined, they can contain large amounts of salts, and small flows may not be easily detected. This is an underlying concern for the environmental sustainability, and a main reason for the search for recycling options.

This report summarizes the current state of publically available knowledge on the salt and water flows as provided by the stakeholders in the Highveld Industrial and mining complex. It summarizes the balances of the water and salt storage and flows. Each analysis of the sources and destinations of salt has been reviewed with the responsible party (industries and DWA). Additional data sets to those provided by these parties have been used. This includes an analysis of the chemical stoichiometry and equilibria in the processes that produce salts and other data from previous studies at these or similar plants in South Africa. This data was typically available at the research institutions.

RATIONALE

In South Africa there is a growing realization of the long term risks resulting from salination of inland water systems. Aspects include long term risks for containment of large amounts of stored salts in the upper reaches of the two main water systems supplying a large portion of the South African economy. In South Africa this long term need and limited availability of clean water for domestic, industrial, agricultural and the natural ecosystems was not fully understood or addressed at the time of establishment of these industries. For example the mining industry commenced prior to the formation of the South African Union in the early 20th century. In the 1980s when most of the current industries were established in the case study area, the water and salt management principle was "zero waste discharge". Consequently large inventories of salts were stored. In 1998 the National Environmental Management Act was promulgated. This included concepts such as "cradle to grave" and "producer pays", and lead to the registration and approval of previously unregistered waste disposal sites. However in 1998 this Act was not applied to the mining industry operated under a separate set of regulations for waste storage and disposal.

It has been proposed by the WRC in this research terms of reference that the problem of large amounts of stored salts can be evaluated using integrated industrial ecology and integrated cleaner production research techniques. The objective is to identify which key factors and barriers to integrated cooperation can be addressed by further research.

These two systematic research techniques work on the principle of continuous improvement of environmental performance. The long term objective of both is a long term match between demand and supply of natural resources. Industrial ecology measures improvement by eco-efficiency, i.e. incremental improvement by economically viable changes in resource consumption. Cleaner production measures improvement in resource efficiency by minimizing consumption of resources in the production of goods and services. The ability of nature to recycle waste and supply natural resources, such as clean water is considered a resource.

Cleaner production also includes the possibility of large scale changes to the production system. This is explained by the Hierarchy of Needs which is discussed in Volume I. The possibilities of redesigning the production system, so as to avoid the waste by changing to another good or service is the first priority. Waste recycling is the second last option. Safe disposal is the final and ultimate task for cleaner production.

In order to establish which projects make the most sense for a company and a group of companies, it is usual to undertake techno-economic assessments and to rank the options in terms of cost and environmental savings. As responsibility for management of the environment is outside the boundaries of a mining or processing site, it lies with the state (in this case DWA for water discharge and clean water supply). The water use permitting authorities have a higher priority on resource conservation and resource protection options than the owners of commercial operations whose priority is economic survival over the longer term. This responsibility for efficient use of financial and manpower resources lies with a commercial enterprise. The mining and processing industries therefore have a higher priority on production output than the resource permitting authorities. Cooperation between the two sets of parties (industry, and permitting authorities) is required in order to establish an improved resource efficiency capability for an industrial complex.

The process for identifying possibilities for environmental improvements commences with an inventory of raw materials consumed and waste produced. This is followed by an assessment of the technologies in use and an evaluation of new technologies which can reduce raw material consumption and reduce environmental impact from waste.

Outputs of the inventory include a summary of the sources and destinations of the waste streams. This assists with the prioritization of the options for investigation of the water based technologies in the production process. Prioritization for cleaner production projects is based entirely on the size of the opportunities for reduction of clean water consumption, and reduction of waste water impact on the environment. Prioritization for eco-efficiency projects is based entirely on the economic improvements to the company by the reduction in clean water consumption, and waste water impacts.

Previous support work in the area of desalination research has been carried out by industry with the intention of producing economically viable products from salt (Roux, 2009; Ras, 2010). This research has neither been proven for commercial operation scale nor has led to a significant reduction to the rate of storage let alone a reduction of the stored mass. Desalination with the intention of producing water at economic cost is a more active research area and has indications of possible economic viability.

Avoidance and minimization of salt production in the mines by ground water pumping, and segregation of fissure water from mine water and ground water pumping above the mine have been identified as possible techniques to reduce the formation of salt in the mines (Hodgson & Krantz, 1998). However, these techniques have been considered to be of limited practicability by the industry, which have other recommendations, for example, the channelling of rain water and filling of depressions so as to promote runoff on the surface above underground working areas. Research on that mine water management was a concurrent project at Sasol mining during this study (Nussey, 2010).

The main tasks for developing integrated technology options for a large and complex inventory calculation of this type are

- Identification of the life cycle of the salt production processes that lead to the large inventory stored in the complex,
- Achieving consensus with each of the participants in the study on the quantification of the salt storage systems,
- Achieving consensus on the long term environmental trends in surface water qualities due to the mining and processing industrial activities.
- Providing a framework for assessing the decision making processes and desalination technologies and their impact on the long term environmental trends in the surface water systems.

OBJECTIVES AND AIMS

The objective of the analysis of the inventory is to understand the key factors that determine the environmental sustainability of the salt storage systems.

Aim 1

To describe and quantify salt and water waste flows; commencing with the identification of the raw materials that become waste, and ending with their disposal and storage. This enables the description of the life cycle of the waste.

Aim 2

To understand the natural and industrial processes that cause the accumulation of salt and waste water. This enables the location and allocation of flows within the life cycle of the waste. This understanding of cause and effect can then be applied with expert knowledge of waters, salts, and industrial and natural processes. This enables the identification and prioritization of eco-efficiency options that have the greatest chance to become integrated projects across the industrial boundaries in the complex.

Aim 3
To understand whether waste from one industry can be used as a raw material in another industry, and what are the main drivers and barriers to implementation of integrated technologies that improve resource efficiency.

METHODOLOGY

Each industry and stakeholder was approached separately with an invitation to participate in the research project, and to discuss the purpose for the research. This included an explanation of the objectives, and the description of the research techniques as were described in Volume I, the Inception Report, and are as follows in brief:

- A 'desired state' consultation procedure in which consensus is built on what constitutes sustainability and the benefits of cooperation. This is primarily a tool of the governance component of the research.
- A 'cleaner production quick scan questionnaire' in which the main flows of raw materials and wastes are listed, and the conversion processes are described. This is the quickest way to link waste flows to raw materials, and industrial operations. It also enables a common understanding of the activities that cause the largest amount of waste. This is a first step to prioritizing interventions to reduce waste and improve economic performance.
- A 'systems dynamics evaluation' to identify waste treatment technologies that produce more waste than they remove. The objective is to identify techniques that reduce salt and water waste.

When agreements had been reached on how to proceed with the data collection and publication of the findings, each industry appointed in-house technical specialists to assist with the data collection and interpretation. These included experts who worked on the site, and experts who worked in strategic environmental planning and coordination at the national level. Mass flow analyses were prepared initially at high level to classify sources and describe processes for generation and disposal of the waste. If there was insufficient understanding by the researchers, or errors in identifying sources and destinations of the waste, the investigation proceeded to a lower level. This process extended for the period 2009 to 2011.

Life cycle assessments require a boundary over which the flows in and out of the system must be balanced. The boundaries are the flows to and from nature, and flows to and from other members of the industry complex.

Waste and non-economic process flows, e.g. slurry water (with salt) for transport of coal fines, are typically not measured reliably, if at all. Achieving a balance of salts over unit operations was not possible with the data available to the water balance flow calculations from each industrial site. For this reason the flows and salt loads were developed over each large unit operation, e.g. coal processing plant. The starting point is available data, which was supplemented with research data or data from other sites. Errors were identified by mass, charge and stoichiometric balances over the full life cycle of the water and salt flow.

Boundaries were established for each industry and for each large operation using the DWA application for Section 21 for water usage, and the company process flow diagrams, and maps. Where flows could not be allocated to any of these sets of information, the flows were classified as unallocated flows. Since storage inventories have not been measured since the start of the industrial operations, it was not possible to estimate all the historical inventories. However it was possible to measure all incoming and outgoing flows and transformations. The unallocated flows were assigned to storage.

Terminology and definitions are important in understanding mass flows over boundaries. A mass flow is a waste when it cannot be used for an economic purpose. If a waste is disposed over a boundary it is “returned to nature”. DWA permits are required for waste transfers between companies in the complex. A waste is stored when it is not discharged, e.g. stockpiled. Liabilities for long term damages caused by waste to the natural systems are a driving force in defining the ownership and responsibility for wastes. The classification of these flows is provided in Sect.21 of the National Water Act (1998).

As this is a multi-disciplinary study reporting norms have been adhered to so as to avoid loss of precision and to enable accurate description of the mass flows. The disciplines used in the preparation of the inventory include geohydrology, process engineering, system dynamics, water quality analysis, environmental life cycle assessments, and cleaner production assessments. The South African DWA definition and measurement methods for reporting of salts (TDS) have been used.

The calculation techniques used to balance mass flows included chemical reaction stoichiometry, equilibrium calculations, charge balance for solutions, elemental mass flow analyses through phase and chemical transformations, consistency with orders of chemical reactions. Verification procedures for the data used in the calculations included a comparison with published research findings, and an audit of measurement techniques reported when key reported data showed internal inconsistencies. All the DWA reported data sets were verified before inclusion in the report. Data from the company laboratories could not be verified as they did not usually provide a 100% salt analysis and it was not possible to carry out quality control tests on the analysis data. Sampling and sample storage procedures were evaluated when there were queries on key measurement reports. The DWA data set over 34 years was tested for self-consistency using ion balances, and found to be the most reliable data set available. Company data sets were typically for a one year period, or a collection of data prepared over 10 or more years.

The chronology of the research is described in Section 3. In summary,

- 2008-2009. Stakeholders were identified and then initiated to the reference methodology for evaluating industrial complexes and the opportunities for integrated eco-efficiency and cleaner production technologies (Brent et al., 2008)
- March 2009. Consultation and data collection commenced at each industrial site. The desired state methodology (Rogers & Bestbier, 1997) was initiated at the same meeting as the cleaner production quick scan procedure. The boundaries and maps for the areas were developed using DWA permits, site layout images from Google Earth, and maps supplied by the industries. Preliminary process flow diagrams were prepared using process descriptions and publications, and waste and water flow diagrams provided by the technical and environmental and water and waste specialists in each industry. The case study area was defined by the boundaries of the water sheds within which the companies are located. For the Waterval River this was the catchment area above the DWA C1H8 priority measurement location. In the case of the Leeuspruit stream watershed, which is a part of the Grootdraai catchment, the DWA C1H5 priority measurement location defines the lower bound of the industrial. These catchments and company boundaries are summarized in Figure 3, and Figure 6. Surface mining by Sasol mining in the Olifant’s catchment is excluded from the inventory.
- September 2009. Company confidential reports were prepared for the boundary condition assessments of the waste production, storage and disposal. Unsustainable processes and key factors for obtaining balance on mass flows were identified with each member via technical project meetings and calculations. The measures of sustainability of systems were demonstrated by examples of positive and negative feedback loops which reduce or increase industrial pollution and discussed. (See also the discussion in Volume III.) The definitions of what constitutes a salt for this study, and how to measure the salts were reviewed and where

calculation errors were identified, the data was excluded from the mass flow measurements. When mass balances could not be achieved, industries were requested to identify any unidentified mass flows of salts and water.

- March 2010. Preliminary findings on the key technical and governance factors affecting environmental sustainability project were prepared and the data gaps on storage and destinations of salts were identified and additional interviews were carried out with the industries.
- February 2011. A consolidated mass balance for each member of the complex, and surface water stream system was finalized after revising the process flow diagrams to include a standardized approach to evaporation, and to include the use of mine water in coal processing. Long term trends were determined in the two main streams draining the study area, i.e. the Waterval River and the Leeuspruit.
- July 2011. Company feedback to the five volumes of the study was provided via the WRC, i.e. following the framework of the desired state methodology. This included some queries on definitions, calculation procedures, provision of additional research data on salt storage capacity of ash. These queries are provided in Section 10, as an addendum to this Volume of the study.
- December 2011 – January 2012. Final review of the stakeholder's comments and this report.

RESULTS AND DISCUSSION

The application of the findings on the mass flows can now be interpreted in the context of the objectives for the study.

Aim 1. Life cycle of the salts in the complex with quantification and locations of sources and destinations

Three life cycles of water salt flows have been identified in the complex (see Figure 5 in Section 4.2). In each life cycle the main cause of salination of water is the reaction between oxygen and sulphide. Acids from this reaction are neutralized by bases from the fissure water flow. Fissure waters rapidly flow down cracks in the strata above collapsed coal mine work areas producing bicarbonates from the reaction of carbonic acid with carbonates. In the open working areas there is an excess of oxygen and only there the acidification of mine water takes place. This on-going process of acid base neutralization results in salts. This continues until base salt flows are halted, e.g. the base minerals in the fractured rock fissures are exhausted, or the acidification is halted, e.g. halt in the flow of oxygen in water and air flows. Acidification then proceeds to a pH dependent upon solubility equilibria of metal salts. (There are a number of very useful discussions in this chemistry, e.g. (Appelo & Postma, 2005a))

Examination of the water compositions indicates that the largest source of the aqueous salts is underground sections of the mine from which water is pumped to allow extraction of ore and coal.

A second and potentially larger cause of salination is the dissolution of mineral salts in coal ash. An upper limit to the amount of aqueous salts that can be released from these ashes has been estimated for ash inventories in Sections 5.2 and 5.4. Sasol advises that their operating limit is lower than this upper estimate (see Section 10). All these salts are contained in disposal sites and the leakage is dependent upon the porosity of the linings and the rate at which unsaturated salt solutions can flow through the disposal site. These flow rates are not known.

A third and site-specific source of salt occurs at Sasol Synfuels. This formation is evidenced by the higher fractions of F, Cl, and SO_4 aqueous ions in the quench unit compared to salts in the mine water and cooling water streams (see Table 8 of the Sasol Synfuels water and salt balance). These salt formation processes are assigned to increased volatilization of halide compounds at gasification temperatures in the Unit, and the oxidation of sulphide gases with quench water to form SO_4.

A fourth salt source is water treatment chemicals used for desalination. This source is approximately half of the mine water salt flows (see Table 1).

The possibility for salt formation from un-oxidized sulphides in the gold mine slimes dams has been considered but is not supported by the mass flow analysis (see discussion in Section 5.6 and flow values in Figure 8). The upper limit for the data set provided by Evander Gold is likely to be around 1 t/d or about 5% of the salt flow for that site. The main causes for uncertainty are unmeasured leaks and the use of an estimate for the evaporation rate in the balance water report for 2009.

Aim 2. Quantification of the salt flows

The summary of the main aqueous salt flows in industry has been consolidated in Table 1. This shows the total load from the site onto the environment is 528 t/d. This is made up from discharges to catchment (56 t/d), storage onsite (424 t/d), and exports (48 t/d).

Sources of salts from natural sources total to 67 t/d from Sasol Synfuels and Eskom Tutuka raw water inflows. Imported salts enter via water treatment chemicals at 155 t/d, and coal water at 5 t/d. The amount of salt stored is not reported in full by the industrial members of the complex and is calculated from the unallocated flows after discussions with the industries and agreement that the flows over the boundary of the industry are correct. Full details of the flows within each industry boundary are found in Table 2 for Sasol Mining, Table 4 for Sasol Synfuels, Table 13 for AngloCoal New Denmark Colliery, Table 15 for Eskom Tutuka power station and Table 18 for Evander Gold.

Process Flow Diagrams allocating destinations of the wastes at industry level were prepared from the unit operations identified with the industries. In the case of Eskom power station see Figure 6, for the water balance, and Figure 7 for flows across the boundaries of the unit operations. For Harmony Gold the flows over each of the unit operations are illustrated in Figure 8.

Total loadings of salts in the ash dumps have been calculated using the upper limit to salt solubility under ash storage conditions. These ash dump loadings are 2011 t/d for Sasol Synfuels (Table 7) and 636 t/d for Eskom Tutuka (Table 14). This is approximately 6 times the aqueous salts stored daily, and provides a total salt load of 3175 t/d for the complex.

The long term trend in surface water flow is increasing salination in the Leeuspruit and the Waterval River. A more detailed assessment of the trends is provided in Section 6. The imbalance between measured industrial discharges and measured stream flows indicates that additional flows have yet to be identified. At issue is the possibility for unquantified and uncontrollable non-point source releases from mines and industries. This issue indicates that a key factor for long term management of environmental sustainability is the uncertainty of leakage and unidentified industrial releases.

An indication of the environmental impact of these unquantified releases is provided by the 34 year trend of increasing salinity downstream from the complex. For the measurement period of 1999 to 2008 the average unallocated load is 56 t/d (see Table 1). That this unallocated load is due to mining and processing discharges is indicated by the increase in Cl and SO_4 over the pre-industrial base line flows (see Figure 9). This increasing salinity accounts for about 6% of the calculated amount of aqueous salts generated by the complex and about 2% of all salts. About 98% of the salts being produced are contained.

An indication of a beneficial environmental impact from the mine water replacement of raw water is the savings in specific water usage for the power station (see section 5.4). For the 2008/9 period at

An indication of a beneficial environmental impact from the mine water replacement of raw water is the savings in specific water usage for the power station (see section 5.4). For the 2008/9 period at Tutuka a specific water usage of 1.9 ℓ/kWh was obtained. The saving of raw water is 0.18 ℓ/kWh. However an indication of the negative environmental impact is mine water production per kWh. Total mine water per kWh is obtained from the discharge amount of mine water for the Tutuka power generated in 2008. This is 0.3 l/kWh based on the daily discharge of 17 Ml/d from the mine head at New Denmark for an approximately 12 kt/d of coal production which is combusted at Tutuka power station see section 5.3 and 5.4,and Table 23.

Aim 3. Can waste from one industry be used as a raw material for another?
Waste salt transfers of 132 t/d gross are taking place in the complex (see Table 1). These are based on contracts mediated by water use and discharge permits. Sasol Mining transfers 49 t/d of salts in 9 Ml/d of mine water to Sasol Synfuels. This mine water is desalinated. The desalination waste is recycled in the ash water system, and disposed in ash dams and evaporation dams.

AngloCoal New Denmark supplies 11 Ml/d of mine water containing 62 t/d of salts to Eskom Tutuka which recovers water for steam production and for Rankine Cycle evaporative cooling. 52 t/d are disposed the ash disposal site and 10 t/d of brine returned to New Denmark from the RO desalination unit underground disposal. These transfers of salts do not account for salt used in desalination.

In the case of Sasol Synfuels 2 tonnes of salt are used in Ion Exchange to remove one tonne of mine water salt. For Eskom Tutuka on average 0.25 tonnes of salt are used to remove 1 tonne of salt. These flows are illustrated in Volume III for the life cycle assessment and Volume V for the discussion on sustainability of the treatment technologies. A mass flow is provided for the each site inventory in Section 5.

The water transfers between the mines and the processing industries account for 3% of the water supply to Sasol Synfuels (Table 9), and 10% of water supply to Tutuka (see Table 15).

The waste water from one industry can be a raw material for another industry, but the waste salt cannot. This is discussed below.

Table 1: Summary of main aqueous salt flows in the industry, municipal and surface water systems in the complex

	Waterval Catchment					Leeuspruit Catchment				
Aqueous industrial salt Inventory daily flows (t/d) (a)	Sasol Mining	Sasol Synfuels	Evander Gold	*Municipal WWTW (b)*	Waterval load (c)	New Denmark	Eskom-Tutuka	Leeuspruit load (c)	Totals for complex	Comments
Salts from underground mine water (d)	214		19			73	76		382	Sources of salts
Salts from chemical processes (e)		49							49	
Salts from raw water		47					20		67	
Water Treatment chemicals		135	0.23				20		155	
Point Discharge to river		9		*9*	18				36	Discharges to catchment flows
Non-point Discharge to rivers (f)					18			20	38	
Total contribution to river salt flow					36			20	56	
Stored (g)	47	349				28			424	Storage of aqueous salts
Imported treatment chemicals and CW (h)		135				5			140	Imported into complex
Saline water and brine transfers (i)	-49 SS	+ 49 SM				-73 ND +10 ET	+ 73 ND - 10 ND		+122 -10	transfers within complex
Exported CW from complex	48								48	Exported out of complex
Contribution to daily complex salt flow (i)	214	230	19			73	40		576	Flow in each industry boundary
Salt flows in each industry daily (j)	214	230	19			78	40		581	Flows determined by production technology and contracts to receive and discharge waste salts (l,m)
Salts produced by each industry (k)	214	49	19			73			355	Flows within the complex boundary

Note a Total calculated aqueous flows for 2008 excluding possible salts flows from the reaction of mineral salts in coal ash mine water or brine in ash storage systems

Note b Municipal WWTW (Wilsenach & Roux, 2008) are not part of the industrial complex but are added to enable a full salt balance on the rivers. Farm flows are not detectable.

Note c Catchment load calculated from measured salt flows less pre-industrialization baseline

Note d Salts discharged from underground = all salts discharged into coal water and mine water

Note e High temperature gasification salts. The possibility of double counting with gasifier ash dissolved in "hot gas liquor" not established.

Note f Non point discharges in 2008 = Stream salt loads in 2008 minus base line salt loads for 1974->1982, minus reported point discharges in 2008, ie, about 3% of total daily flow.

Note g Salts stored are not measured. Storage = mass imported + mass generated - mass exported over an industry boundary.

Note h Industrial salt flows imported over the complex boundary

Note i NewDenmark receives coal water from other coal suppliers at its stockpile for Tutuka power station

Note j Industry salt flow within boundary of the industry= sum of salts from consumption (mine water + raw water + treatment chemicals) + salts produced

Note k Industry production = salt production inside industry boundary

Note l For example, if desalination technologies were replaced by lower salt consuming water treatment technologies, the contribution by that industry to the salt load would fall 155 t/d

Note m New Denmark mine supplies approximately 40% of Tutuka coal, and is responsible for managing the stockpiling of 60% of coal imports to the complex for Eskom.

Key factors affecting the environmental sustainability of the salt storage systems

The long term trend on increasing salinity in the surface water systems due to mine water salts indicates that the issues of mine water salination and salt storage are key factors in the long term environmental sustainability of the region. For salt storage, research is being carried out in ash storage and underground storage systems.

Seven candidate salt disposal and storage systems are in use

- Brine is mixed with fresh ash in a “dry system” at Eskom with continual irrigation of brine water on the dump site. Limited leachate is produced. Research is directed to stabilization of the salts via chemical and physical processes such as mineralization and precipitation of the salts.
- Brine is mixed with ash in the Sasol “wet ash system” where a large amount of leachate is produced as “ash water” which is desalinated to produce process water. Research at Sasol is also directed to stabilization as with the Eskom storage sites.
- Evaporation dams are either lined, or unlined with leachate recovery systems. Advise has been these storage systems are not being actively researched as in the case of ash salt storage systems, and underground storage systems.
- Slimes dams for gold mine tailings,
- Underground disposal of mine water in coal mines,
- Underground co-disposal of brine with mine water recharge of coal mine compartments.

Other disposal mechanisms for saline water available to the mines include,

- Dust suppression of coal stockpiles with spraying of mine water,
- Fine coal discard and coal rock co-disposal sites which using slurry transport of sub 100 µm fines, and evaporation of the slurry water,
- Dust suppression of working areas, e.g. coal processing areas.

The long term trends on storage capacity, loading, and leakage for these disposal sites are not available in the public domain and cannot therefore be linked to the long term trends of surface water salination. Therefore additional public domain information is required in order to establish the viability of the two disposal options currently being researched by industry, i.e. optimized ash disposal systems, and underground containment.

> ***The first key factor is therefore the monitoring of the integrated environmental performance of the case study region, and the identification of projects that will halt the increasing trend of salination of the surface water system. These will include projects to locate and monitor the non-point sources of salt release in the system.***

Leakage data is available for aqueous salts from gold mining slimes dams (Section 5.6). Storage capacity in a slimes dam is higher for Ca, Mg and SO_4, than Na, K, Cl, and F. This is consistent with the solubility data. Storage capacities for these salts are also higher in ash-brine co-disposal sites as reported Section 5.2. However, the correlation with this storage capacity and diffuse source discharges of TDS flows in the Waterval and Leeuspruit has not been made.

Any viability of a candidate eco-efficiency project requires that economic efficiency is demonstrated. However, any integrated eco-efficiency projects which replace one storage system with another should be quantified in order to enable integrated project sharing of environmental costs and risks.

> ***The second key factor is the provision of engineering performance data for each candidate disposal technology. This will quantify the amount of salt from mine water that can be stored in each of the candidate aqueous salt storage systems.***

Key factors affecting the adoption of integrated eco-efficiency projects in the case study area.

The experience of the mine water desalination project can be used to understand how integrated eco-efficiency projects in the area can develop and can be improved.

Two integrated project agreements have been made. One between DWA and Eskom, Tutuka and AngloCoal, New Denmark, and one between DWA and Sasol Synfuels and Sasol Mining. These agreements have been consolidated into the water use permits under section21of the NWA. These permits specify upper limits to the amount of raw water that can be replaced by mine water. The intentions of the agreements are to recycle mine water. However the agreements have not been linked to long term salt absorptive capacity on the Sasol Synfuel and Eskom Tutuka ash disposal systems which were established in the 1980s for disposal of salt in process waters.

What appears to be missing from these project agreements are:

- High level regional overview and agreement on the viability of technical and economic alternatives to the increasing demand for processing industry support to mines for recycling of excess mine water flows, and the subsequent safe storage and disposal systems, e.g. in the ash and underground disposal systems, and
- Understanding of the long term environmental sustainability for the practice of replacing raw water with mine water. It is shown in this inventory that use of mine water adds more salts to the industrial plant storage systems, i.e. the 20 Mℓ/d of mine water contains 110 t/d of mine water salts, and replaces 20 Mℓ/d raw water which contains 5 t/d of natural water salts.
- Upper limits to the capacity of salt ash storage systems to store the additional salts from mine water.

As is now shown in this study, high level understanding of impacts and potential for integrated technologies is assisted by an integrated assessment of the sources and destinations of salts, i.e. a life cycle assessment of flows of salts and water, within the complex, for the period of the analytical data provided by the industries, i.e. a water flow year around 2008.

It also appears that any economic and environmental cost benefit study preceding these permit changes did not integrate salt storage with an assessment of alternative water supply options. For example other options for reclamation of this 20 Mℓ/d of mine water have not been identified during the study, e.g. municipal water supply. Reports on options for reduced mine water discharge have not been proposed as alternatives to reduce the salt storage problem. It is concluded that a long term model for economic and environmental sustainability has not yet been considered for the public domain for this complex. As salination of fresh water resources is a national issue, the learning from such a case study would extend beyond the needs of the individual industries and the regional interests of DWA in this study area.

A framework for development of integrated eco-efficiency project has been proposed for South Africa (Brent et al., 2008). A schematic of the model is given in Figure 12. A discussion on the application of this model to this case study is provided in Section 7.6. Each industry has committed to the principles of continuous improvement of resource use efficiency (Anglo American, 2010b) (Sasol, 2010) (Harmony Gold, 2010) but economic incentives and improved environmental sustainability are not linked to reductions in operating costs and post-closure liabilities for waste salt and saline water storage.

These observations lead to two additional key factors

> ***The third key factor is the need for data which demonstrates to the DWA and to industry those eco-efficiency technologies where profitable business can be made***

from salt waste management. Such data will assist industry to make technical decisions on how to proceed with and to prioritize options for improved environmental performance.

The fourth key factor is the application of controls on access to resources, with the objective to increase the value actions to improve cleaner production, e.g. avoidance and recycling. These controls will enable industry to decide on how to improve economic performance using the available options to improve environmental performance.

RECOMMENDATIONS FOR FUTURE RESEARCH

The following activities are proposed to improve the value that can be obtained from this storage and flow inventory, and for the development of integrated projects.

- An economic framework for eco-efficiency similar to that in use for the energy sector (e.g. REFIT and Eskom Energy Efficiency incentives) should be evaluated as a case study in this area. This could be a national pilot. The advantages include three multi-disciplinary companies who have R&D capacity. AngloCoal has already developed a techno-economic framework for its water reclamation demonstration project near Witbank. This is discussed in detail in Volume V. Indications in Volumes I, III and V of the study are that raw water is currently too cheap to make desalination an economically viable business in inland water. In comparison desalination costs for sea water conversion to municipal domestic and industrial water supply are increasingly economically viable at coastal regions on the west and south coasts of South Africa. Those municipalities do not have access to an extension of the Lesotho Highland project, for example. However waste disposal for seawater desalination does not pose the same environmental risk as does inland disposal to the inland water supply systems. This difference in environmental risk illustrates the importance of management of the inland salt disposal problem.

- Economic offerings for safe salt disposal technologies with verified and traceable management techniques should be made available to the public, industry and the DWA. It is hypothesized that when the costs of safe disposal and desalination are comparable to raw water charges then a clearer case for integrated eco efficiency projects will be made.

- The risk of leakage from the storage sites must be quantified. It is expected that each industry should have large amounts of data on diffusion profiles and leakage from current storage sites. This data can be compared with existing or new DWA priority measurement data sets. The possibility of leakage from underground mine sites must be eliminated in order to make underground disposal of brine a viable disposal option.

- Alternatives to recycling for integrated projects should be considered. These alternatives can be tested using the economic framework that is recommended above. Additional data sets, e.g. quantities and costs for reduced salinity mine water will most likely be required. These environmental and techno-economic assessments should provide further options from the cleaner production hierarchy, i.e. avoidance, minimization, reuse/recycling, and safe disposal.

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a	annum=year
AW	Air Water in mine ventilation system
bal.	Balance
BFW	boiler feed water
BW	Brine Water
Ca	calcium ion
Cl	chloride ion
CP	Cleaner Production
CSIR	Council for Scientific and Industrial Research
CW	Coal Water
CW	Cooling Water
d	Day
Demin.	Demineralisation
DWA	Department of Water Affairs
EC	Evaporator Crystalliser desalination
Evapn.	Evaporation
F	fluoride ion
FW	Fissure Water
GWh	Giga watt hours
HCO_3	bi-carbonate ion
HLS	Hot Lime Softening desalination
IE	Industrial Ecology
IX	Ion Exchange desalination
K	potassium ion
kt	kilo-tonne
kWh	kilo-Watt hour
ℓ/uso	litres of water consumed per Unit kWh Sent Out
m	Meter
Mg	magnesium ion
mg/ℓ	milligrams per litre
Mℓ/d	mega litres per day water flow
MW	Mine Water
MW/kWh	Mega Watt per kWh
Na	sodium ion
NCPS	National Cleaner Production Strategy
NEMA	National Environmental Management Act (1998)
NH_4	ammonium ion
NO_3	nitrate ion
NWA	National Water Act (1998)
pH	concentration of hydrogen ion to the negative base 10
PO_4	phosphate ion
PW	Potable Water
Rain W	Rain Water

RO	Reverse Osmosis
RQS	Resource Quality Services
RW	Raw Water
SAWS	South African Weather Service
SD	Slimes Dam
SM	Sasol Mining
SO_4	sulphate ion
SS	Sasol Synfuels
SW	Surface stream Water
t/d	tonnes per day mass flow
TAL	Total Alkalinity
TDS	Total Dissolved Salts
UCT	University of Cape Town
UKZN	University of KwaZulu-Natal
VE	Vacuum Evaporator desalination
WA	Water Act (1956)
WRC	Water Research Council
WW	Industrial Waste Water
WWTW	Waste Water Treatment Works
µm	micro-meter = 10^{-6} m

1 INTRODUCTION AND OBJECTIVES

1.1 Inland salt storage and key issues in SA

This study reports on the findings of the research on the key factors affecting the use of an inventory for the establishment of integrated eco-efficiency projects where one industry's waste is another industry's raw material. The inventory is prepared on the water and salt flows within and between industries in the case study area. The industries are located above the Highveld coal field in Mpumalanga.

2 APPROACH

An assessment of the salt storage capacity in each of the industrial members of the complex is made using the supplied mass and flow data provided for each of the sub complexes identified. This is compared with the observed surface water flows which have been obtained from the Department of Water Affairs' integrated water quality management system data base.

The data collection methods and findings are taken from the findings of the survey inventory and interviews with the stakeholders.

Two types of storage have been identified.

- Underground storage which includes the dissolved salts contained in all the closed mine working areas. The amount is calculated from the analysis of the total dissolved salts (TDS) using the DWA definition of dissolved major salts, i.e. the water sum of the concentrations of cations Ca^{2+}, Mg^{2+}, and Na^{+}, and the anions for Cl^{-}, F^{-}, sulphate, and bicarbonate, nitrate and ammonia, and phosphate.
- Above ground storage for the total dissolved salts is calculated from the analyses of the process water, and waste water storage inventories. In addition, the water soluble salts are estimated from the compositions of ash in the dumps.

Surface stream data is taken from the surface stream flow inventory report. The total dissolved salts are calculated using the DWA water quality laboratory quality system data and the DWA integrated water quality management system and water flow data bases.

The questions asked are "What salts are being released into the environment? Does industrial input to stream compare with the measurements?

3 METHODOLOGIES

3.1 Identification of boundaries for integrated project development

A method to assess sustainability of multiple technology energy supply (Brent & Rogers, 2010) for renewable energy systems in rural South Africa has proposed that a learning method be used to identify ways to improve techno-economic and environmental sustainability. This involved the owners and beneficiaries of the renewable energy system, as well as a multi-disciplinary expert team. A key component is the establishment of the boundaries of the common system for which the conditions of sustainability was met for the conditions of sustainability in governmental, economic, and resource flow systems (Rogers and Brent, 2008). The technique by which an initial set of boundaries are established is defined in part by the questions that are being addressed by the study. These include who is responsible for the liabilities associated with each waste? Can recycling of waste between neighbouring industries be encouraged by regulations and economic incentives? Is this environmentally sustainable? In this study, for example, the underground and surface water system has been defined by the catchment boundaries. Reasons for this include the observation that ground water flows are strongly correlated with the catchment flows, and the intention of the study to the impact on the catchment water supply. The other natural resource is coal. However it is not the primary objective of the investigation. But the mine leases are used to control ownership of the coal. These set the boundaries between the collieries and the energy processing plants (coal to liquid fuel and coal to electricity).

Time for decision making in the social system has been identified as the time boundary. Four generations or 100 years can be considered the maximum limit of planning in the South African social system (Rogers and Brent, 2008). Industry representatives indicate that the planning horizons are based on the economic productive life of the processing plants (40-60 years), and the estimated economic life of the mine. At one stage during the project the gold mine reported planning from weeks to a few months depending on the gold price and the electricity price. The coal mines reported planning of the order of 40 years. The history of the industries goes back to the 1950s for the gold mining, and the 1980s for coal mining, electricity generation and synthetic fuel production.

A technique for establishing the sustainability of a natural or industrial or social system has been proposed in the governance study (Volume IV). It is based on systems dynamics (Systems Dynamics Society, 2008; Forrester, 1968b; Forrester, 1968a) and uses the concept of controlled systems which operate from set points and positive and negative feedback loops. For example a desalination plant that operated with a positive feedback loop produces more waste than it removes. The governance study has highlighted this aspect of un-sustainability. For example, ion exchange produces three tonnes of salt to remove one tonne of salt from incoming water flows.

Time scales for sulphide mine water salination have response times that range from tens to hundreds of years (Banks et al., 1997a). Business cycles are typically over the life of a plant or mine. These can extend from 10 to 40 years. There is therefore a role for the authorities to stabilize business use of environmental systems by way of taxes, penalties and incentives.

3.2 Selection and quantification of key flows

A life cycle approach has been used to identify the causes of the saline flows and to identify the final destinations of the flows on the sites of the members of the complex. Company specific data has been assessed for the annual reporting periods between 2008 and 2010. The possibility of flows from the storage areas to the surface water has been tested with an assessment of the surface water flows leaving the complex for the period of the available DWA water quality records, i.e. mid 1970s to 2008. Indications of the agreed limits to flows are provided via permits and invoiced water flows. Flows inside the boundaries are typically estimates based on design intent and crosschecked with observations. Observations from the site work show that the plants have been typically designed and maintained for flow measurements of parameters that affect economic performance. Water is used for process control, and flows can be estimated from production flows. Waste can also be estimated from production flows, but compositions are not measured continuously so the salt flow estimates and waste water flow estimates are used for the flow calculations. Over a material life cycle, transformations of the mass flows can occur. In the case of water, these are transformations from liquid to gas, water as a reagent for production of, and water as a by-product of Synfuel production. In the case of salts, transformations are from reduced to oxidized states, and from solid to aqueous solution, and from solid to gas to aqueous solution, and from aqueous solution to mineral. Mass flows over these transformations are large and are required in order to understand and verify flows within the member site. The approach has been to use the company specific flow diagrams and to obtain mass balances over the unit operations. Assumptions for each site have been discussed with the company representatives.

3.3 Salt flows

The measurement of salts has been an area where there was initially no clear consensus among the stakeholders and members of the complex. In physical chemistry a salt is typically water soluble and dissociates to free anion and cation species once in solution. Minerals are formed from these ions when the solubility of combinations of the ions exceeds the solubility of the mineral for that particular combination of ions. In the cases of acidic and basic solutions, these ions include species described most simply as H^+ and OH^-. Some minerals, e.g. silica, are soluble in water but do not dissociate into ions. These are not salts. After discussions with all stakeholders the measurement of salts in solution was taken to be the sum of total dissolved salts (TDS). This contrasts with the uses of TDS for the Total Dissolved solids, e.g. USGS,(Hem, 1985) TDS is measured by analysis of the following ions Na^+, Cl^-, K^+, Mg^{2+}, Ca^{2+}, Cl, SO_4^{2-}, HCO_3^-, NO_3^-, F^-, PO_4^-, NH_4^+ and total alkalinity (TAL) (Louw, 2010). For some members of the complex salts were mainly the highly soluble ions, e.g. Na, K, and Cl. Total alkalinity which is measured as $CaCO_3$ by acid titration is converted to carbonate and bi-carbonate concentrations using equilibria constants (Hem, 1985), and are typically excluded from the industrial analyses as these are not considered environmental pollutants.

3.4 Boundaries for decision making

Institutional cooperation is required for transfers of waste flows over boundaries. Wastes that can pollute are assigned responsibilities under the National Environmental Management Act. One of these principles is the coordination of responsible parties who are affected by the life cycle of the waste stream using the best practicable environmental option methodology (Rogers and Masekoameng, 2008). The owner of the ground on which the waste is generated is responsible for the safe waste disposal (Rogers et al., 2008).

3.5 Boundaries for an integrated Eco- industrial system

The possibilities of industrial eco-efficiency at the level of integrated complex, as distinct from the level of an operating unit have been given priority in this study. The term “eco-efficiency” is sometimes taken as synonymous with the term cleaner production. But the two terms have differences. These are based on the intention of the study. Eco efficiency is used to describe industrial sustainability. Continuous improvements in resource efficiency are made with the ultimate objective of matching resource consumption with the earth’s carrying capacity (Rogers et al., 2005). The measurements are made through the life cycle of a product or process. Cleaner production intends to design industrial processes and consumption with the constraints of the ecosystems that support the industry and society. In South Africa, a national cleaner production strategy has been proposed (Rogers et al., 2005) with the mission statement in Figure 1. A concept for regional and integrated approach to industrial ecology in South Africa is described by Brent (Brent et al., 2008) in Figure 1. Opportunities for improving efficiency include reuse or recycling of waste streams in the context of enabling governance mechanisms. These enabling factors include penalties for exceeding environmental targets or incentives for improved resource efficiency. However within the scope of work for the study which excludes economic assessments, the viability of Eco-efficiency is not measurable as there is no economic driver included in the scope of work. The focus is therefore on integrated cleaner production options which can have a measurable environmental efficiency (see Figure 1). The opportunities for these should be more easily identified within the large range of options that become available from the complexity of shared water and salt flows between the large industrial and mining complexes. The boundaries of the integrated system are therefore the boundaries of the members of the complex, and the measurement points for the environmental efficiency.

Mission Statement for National Cleaner Production Strategy
"Adopting the principles of Cleaner Production, i.e., continuous application of an integrated and preventative strategy applied to products, processes, and services so as to increase eco-efficiency of reduce resource usage, risks to humans and the environment, by using a full life-cycle approach"

Figure 1: South African Strategy for Cleaner Production

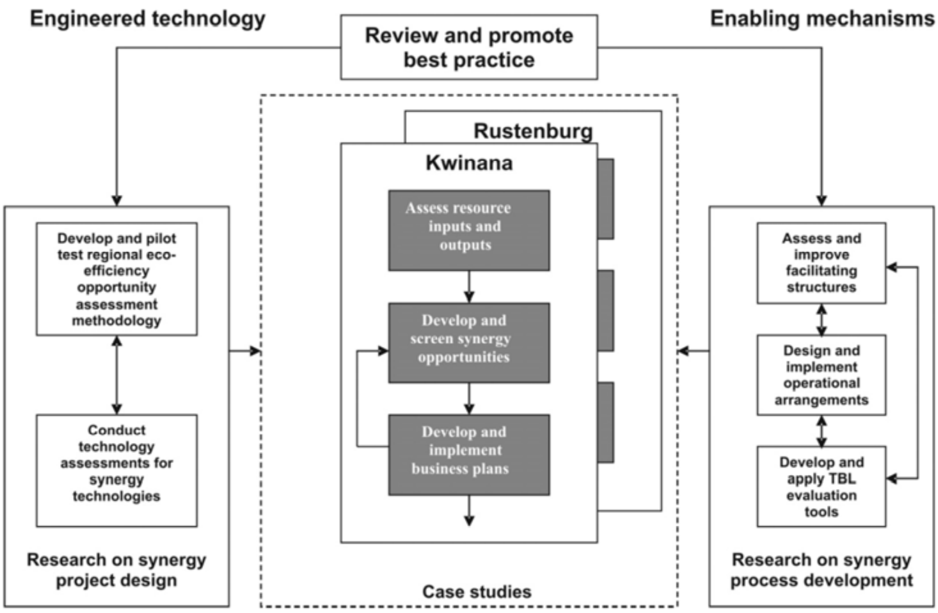


Figure 2: Research needs to review and promote best practice of industrial symbiosis (Brent, 2008.)

3.6 Inventories

A life cycle of the flows was made within the boundary of each member of the complex. This was used to understand the sources and destinations of the flows and to enable a balance over each of the operations where a transformation of the flow took place. Examples of transformations are the change of water flow from a liquid to a gas which occurs at the disposal sites where saline solutions are used for dust suppression and for maintaining coal moisture in the nominal range between 6 and 8% by mass. Transformations also take place where the water flow changes to another classification due to the ecological or industrial process that it is subjected to. Example is the flow of ground water into a mine working area. The ground water can be mixed with mine water, or can be exposed to sulphide minerals and oxygen and bacteria and be converted to mine water. As the inventory preparation is part of the establishment of the options for integrated technologies the consultation process used for establishing perceptions and identification of possible integrated projects, the consultation process for inventory preparation was coordinated with the objectives of the governance study interviews (Volume IV). Water flows are pervasive to all mining operations and most industrial processes. The approach was to take a high level holistic flow analysis. This was refined as needed for understanding of sources and destinations and bio-physical processes of production, absorption, and dispersion of the water and salts. The summary of the high level flows is provided in the life cycle flow.

The inventories of the mining and processing industries are summarized in the context of storage capacities for water and the major cations and anions used to assess surface water quality. These are compared with the surface water inventories in the context of long term trends in the two main streams draining the study area, i.e. the Waterval River and the Leeuspruit.

3.7 Summary

The objective of this assessment is to develop an inventory of raw material consumption and waste production so that the environmental sustainability of regional cleaner production possibilities can be identified. The environmental life cycle approach enables the identification of the primary causes of environmental impacts.

4 RESULTS

4.1 Boundary of the proposed Highveld Industry and Mining complex

The case study area has been defined with the stakeholders using boundaries of the mining leases, the Section 21 regulated water and waste activities, and the catchment boundaries of the Waterval River and the Leeuspruit surface water system. The complex is located above the Highveld coal field (Barker et al., 2000a), which is in turn above the eastern edge of the South African deep mining gold complex. Boundaries of each of the members of the complex, and the catchment are indicated in Figure 3 below. Measurement points for loading of the surface water system are the DWA flow and water quality monitoring points marked C1H008, and 177962. The latter point is also numbered C1H5. It has been found that the case study complex can be described as a set of sub-complexes. These are:

- The urban industrial complex composed of Secunda, Evander and Embalenhle residential areas with the associated light industries that support the following major industrial complexes.
- The Harmony Gold Evander complex which contains three operating shafts, three slimes dams, a concentrator processing plant, and the Leeupan evaporation dam.
- The Sasol industrial and mining complex containing the Sasol Synfuels and associated processing industries and the Sasol mines which are located in the Waterval and Leeuspruit catchments.
    - o The Sasol Mining site is adjacent to the urban complex and above part of the underground gold mining operations. It contains four operating underground coal mines, a coal processing plant which supplies coal for export, coal for the Sasol Synfuels gasifiers, electrical power station, and process heat boilers. It currently stores saline water underground in four mines, and above ground storage in four surface dams. Salt minerals from evaporation of saline water are stored in the discard coal and mine rock dump.
    - o The Sasol Synfuels complex contains the coal gasifiers and the gas to liquid Fischer-Tropsch plant and the 600 MW power station. The complex contains downstream processes which use by-products from the coal and gas to liquid fuel plants for production of fertilizers, and explosives. A speciality bulk chemical business provides monomer and polymers. The site contains numerous currently operating and closed waste disposal sites for saline and mineral salt disposal. Salt co-disposal with ash (Mahlaba et al., 2008) is used with the fine and coarse ash disposal sites. There is also integration of waste disposal with Sasol Mining.
- The Eskom and AngloCoal coal to electricity complex comprises the Tutuka power station and the AngloCoal New Denmark colliery.
    - o AngloCoal New Denmark colliery includes three shafts, of which two are the main production conduit to the working compartments. The coal is supplied to Tutuka

power station by conveyor belts. Coal from other mines is supplied by truck to a coal stockpile and discard site. The colliery has underground storage of mine water and underground storage of brine from Eskom desalination plant.

- o Tutuka power station is integrated with the AngloCoal New Denmark colliery. The colliery manages all the coal supplies on their lease area and manages the coal stockpile which is outside the mine lease area. The stockpile has a fine coal discard area. The mine supplies mine water to ESKOM. The mine salts are desalinated for cooling water and for boiler feed water. The resultant brines are disposed with ash in the Eskom ash disposal site and underground in the colliery brine storage compartment.

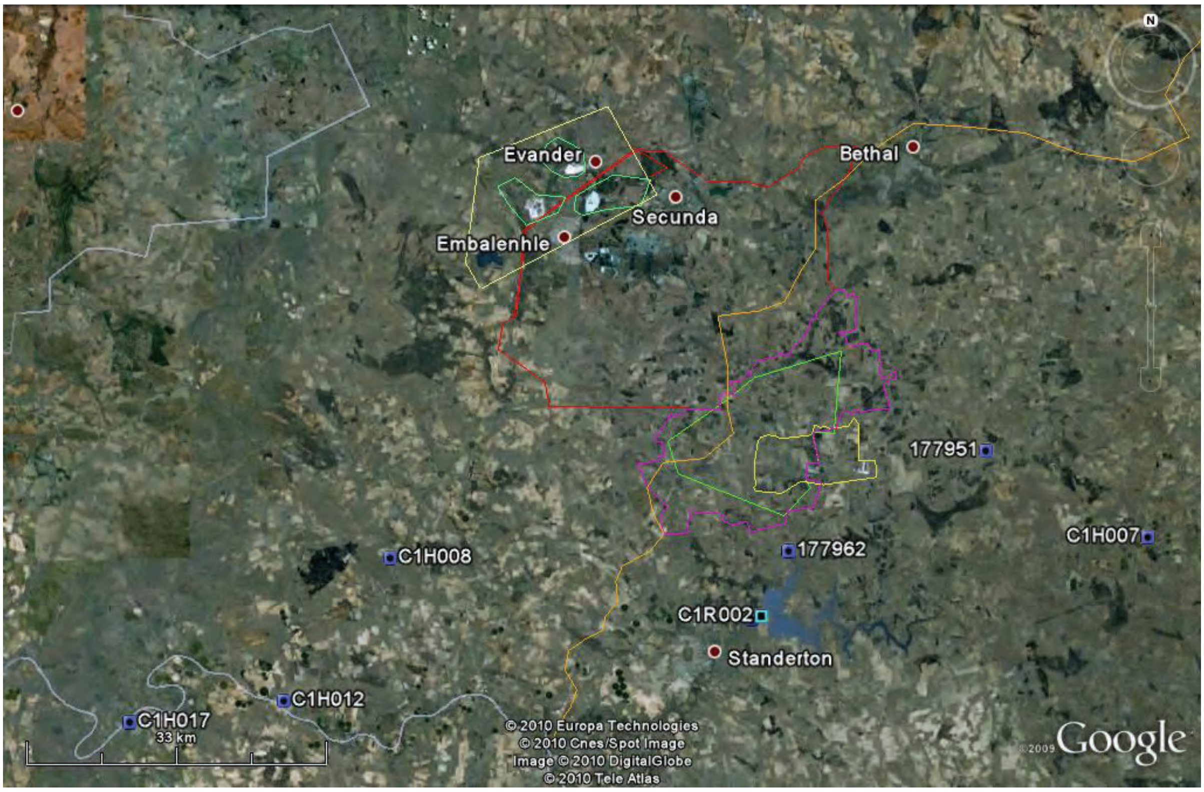


Figure 3: Boundaries of case study area, watershed and priority measurement locations

Note: Locations of members of the complex are from top left, Harmony mine (yellow) with 3 shaft complexes (green), Sasol Synfuels, Sasol Mining (red), watershed Waterval and Grootdraai (dark yellow), AngloCoal-New Denmark (purple) with the underground mine areas (green), ESKOM -Tutuka (bright yellow). DWA sampling stations begin with C. Mpumalanga sampling stations begin with 1. Sampling station C1H5 is superimposed by sampling station 177962.

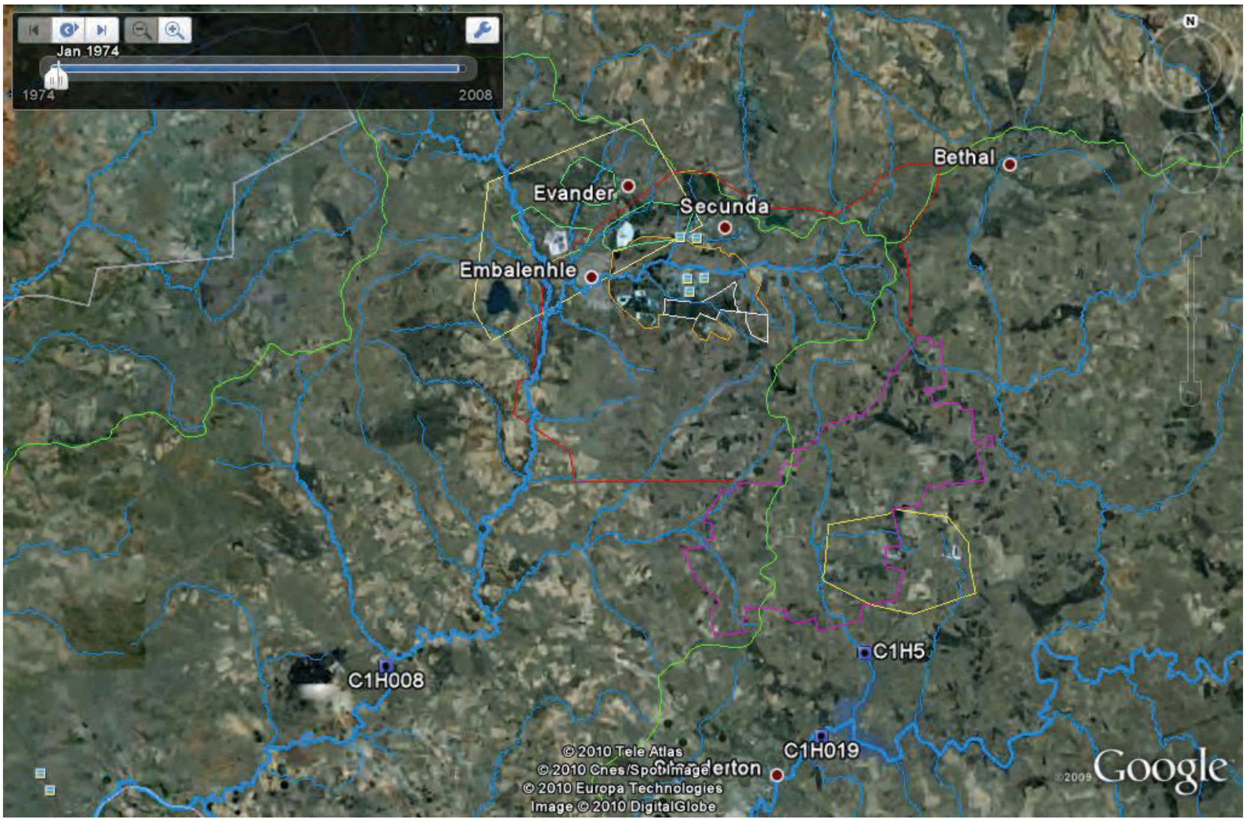


Figure 4: Waterval River measurement station C1H008 and Leeuspruit measurement station C1H5, and Vaal River Measurement station C1H019

Note: Boundaries of case study area, watershed and priority measurement locations from top left, Harmony mine (yellow) with 3 shaft complexes (green), Sasol Synfuels (orange), Sasol Mine working leases (red) Sasol Mining coal and mine water processes (white), watershed boundaries Waterval River and Grootdraai (green), Anglo Coal-New Denmark lease (purple), Eskom -Tutuka (bright yellow)

4.2 Life Cycle of water and salt flows

In order to obtain a qualitative understanding of the flows of salts and saline waters for the complex a review has been carried out. This included the WRC research on coal mines in the area, (Hodgson & Krantz, 1998; Appelo & Postma, 2005b); (Pulles et al., 2008; Pulles et al., 2008; Wimberley et al., 2008; Pulles et al., 1995). The current international literature on the chemistry of saline mine water reactions was reviewed. This research provides an understanding of the main ecological processes that take place when a previously reducing environment is transformed into an oxidizing environment by the addition of oxygen in air and carbon dioxide in water into the ground water and mine working area (Appelo & Postma, 2005b; Stumm & Morgan, 1996; Stumm & Morgan, 1981; Hem, 1989; Cornell et al., 1989; Kirby & Elder Brady, 1998; Banks et al., 1997; Banks, 2004)(Wimberley et al., 2008).

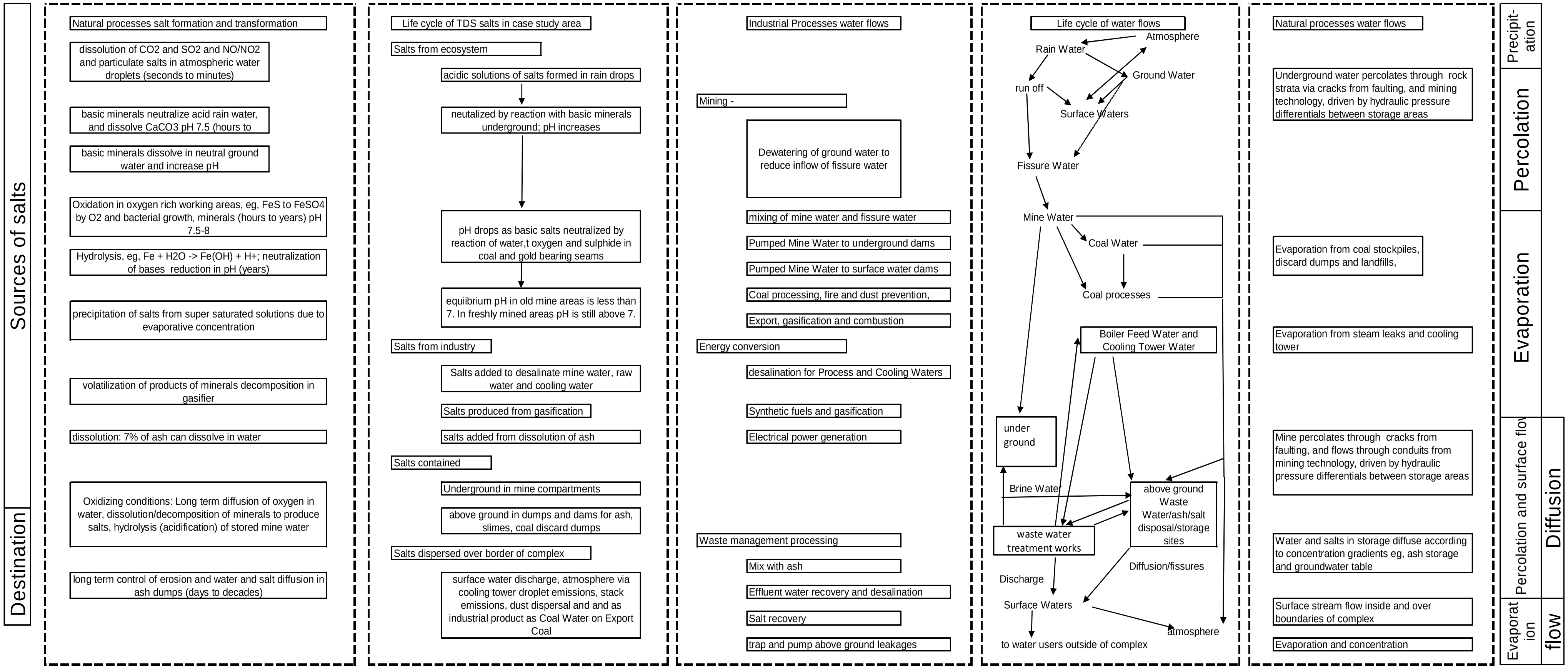
This understanding has been used to interpret the observations and data provided by the members of the complex. A life cycle flow of the water and salt has been used to explain the flows of water and electrolytes as the water moves from ground water to mine water to an evaporation site. The salt moves from the mineral to a solution and then to a mineral at the evaporation site. The steps assigned to this life cycles are described below and illustrated in Figure 5:

1. Rain water percolates through the soil and rocks and becomes ground water which is of a quality that is acceptable for agricultural and domestic use. When this ground water percolates through the cracks in the rock strata into the gold mining compartments it called fissure water. The two DWA boreholes in the region indicate quality of fissure water, i.e. pH between 8.1 and 8.3, with a TDS between 760 and 960 mg/ℓ. When fissure water inflows are strongly correlated with rain, low salinity has been observed (Hodgson & Krantz, 1998). The

mines report highest fissure water flows occur when it rains. For example, fissure water at Evander Gold has been found to have a pH of 7.15 and a TDS of 258 mg/ℓ. Fracturing of the rocks above the mining compartments depletes the ground water supply. The affected farmers are provided with piped water for domestic use and animal watering. This supply is a condition of the mining permit.

2. Most fissure water flows are not separated from mine water and the sulphide minerals which react with oxygen and bacteria to produce more mine water. Potable water is used with mining equipment and also becomes mine water. The annual average daily mine water flows is of the order of 76 Mℓ/d. For coal mines the pH is observed in the range 6.7 and 8.5 with TDS between 3 000 and 6 300 mg/ℓ. For the gold mine pH is observed in the range 4.6 to 8.4 with TDS between 2 400 and 2 659 mg/ℓ. The transformation of fissure water and ground water to mine water is the main cause of salination. Data on the reaction times has not been provided, but is strongly catalysed by the presence of bacteria, and the amount of salination can be reduced if the water is removed rapidly from the work area (Hodgson & Krantz, 1998; Appelo & Postma, 2005b; Wimberley et al., 2008; Stumm & Morgan, 1996; Stumm & Morgan, 1981; Banks et al., 1997; Banks, 2004; Stumm, 1987).
3. Mine water daily flows exceed the rate of coal extraction, so most of the mine water is pumped from the working areas where it is used by the colliery for coal and waste coal processing and evaporated leaving behind mineral salts. These activities include washing to remove fines and coal rock dust, grinding, waste coal beneficiation stabilization of fines in pastes, and for slurry transport of fines (< 0.5 mm diameter particles of rock, coal, and low CV coal discards). A surface water content of between 6 and 8% mass-water/mass-coal is maintained for safety to prevent self-ignition and explosion of fine coal dust. This water is called coal water.
4. Process cooling water and boiler feed water are produced from mine water and raw water. Grootdraai dam supplies raw water to the complex. The main purpose for the raw water is to supply evaporative cooling so as to remove waste heat. Thermal efficiencies of the Tutuka power station are about 32%. The remaining 68% of the energy must be removed, and this is mainly achieved with large quantities of water. Mine water is also desalinated to produce boiler feed water which is used for heating and cooling at Sasol Synfuels. Steam is used to transfer energy from one process to another. Mine water is also used to reduce raw water consumption. The technologies used to remove salts are hot lime sludge precipitation, reverse osmosis, vacuum evaporation and condensing, and ion exchange at ESKOM. At Sasol Synfuels, desalination technologies are electro-dialysis reversal, vacuum crystallizer and condenser, reverse osmosis, and vacuum evaporation, and ion exchange.
5. Desalination waste includes sludge, saline water, and brines. Less than 6% of the salts can be considered recoverable for commercial use. These are NaCl for the chlorination plant, Na_2SO_4 and $NaCO_3$.
6. Saline waste is typically concentrated into brine and co-disposed with ash. When the amount of salt is in excess of the long term absorption capacity of the ash, special permits can be obtained for alternative disposal procedures, e.g. as brines in underground colliery compartments.

Life cycle of salt and water flows in the case study area



Note: DWA Definition of TDS is the K, Na, Ca, Mg, Total Alkalinity/HCO3, Cl, SO4, F, PO4, NH4, NO3

DWA-RQS, Calculating derived variables *RQS Quality Manual.* 2010 edn. Pretoria: DWA-RQS, .

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Figure 5: Life cycle of water and salt in the case study complex

5 INVENTORY RESULTS, TREATMENT OF RESULTS AND DISCUSSION

The major portion of waste salts generated by the various industries in the complex are, by design intent and the water use and waste water permits, confined within the boundaries of the system. Flows to the environment are mostly unintended, and consequently not explicitly reflected in operating data supplied by the industries.

5.1 Sasol Mining Collieries

The boundaries of the Sasol Mining study area are based on the mining lease boundaries (Barker et al., 2000b) and the Section 21 activities. As the boundary of the case study area is based on the Vaal Catchment, the surface water flows, and storage areas in the Oliphant's catchment are excluded. Drainage of the lease area in the Vaal catchment includes the Waterval River, the Leeuspruit and the Blesbokspruit. Sasol Mining advises that there are currently no mining activities drained by the Leeuspruit and the Blesbokspruit and no discharges to the Vaal catchment area. The only discharge is to Sasol Synfuels (Nussey et al., 2009).

The range of activities leading to the generation, storage and discharge of salt and water were identified during discussions with the representatives of Sasol Synfuels, and Sasol Mining. In terms of the NWA the Sasol Mining inventory covers the Section 21 activities for storage of mine water above and below ground, extraction of mine water, the disposal of wastes that can affect receiving water bodies, and discharge onto the Sasol Synfuels site. The main water consumption on the site is for coal processing using mine water. This includes; recycling of coal discards by milling and gravity separation; transport of fines in slurry and paste form to avoid the large scale losses to dust from dispersal of sub 500 micro meter coal; beneficiation of raw coal to improve calorific value for export; dust suppression of stockpiles, coal processing sites, and coal discard disposal sites.

Sasol Mining supplies coal to Sasol Synfuels by way of two stockpiles located on Sasol Mining site and immediately adjacent to Sasol Synfuels small coal processing plant. Coal is extracted as needed from the Sasol Mining stockpile and distributed to the processing plants. The main processes are gasification, and steam and electricity power generation. The life cycle for the Sasol Mining salt flows begins with the inflow of water to the underground mining area, and ends with the discharge of mine water into Sasol Synfuels, and the transfer of coal water to Sasol Synfuels, and to exported coal, and the disposal of coal discard slurry and coal rock on the coal discard land fill site. All the salts are transported in water. The salts are trapped as minerals at the locations of coal water and mine water evaporation. A white gypsum deposit can be observed where the salts have accumulated and the water has evaporated. Mine water evaporates at the coal discards landfill, coal stockpiles, dusty work areas, and the mine water storage dams.

A company report on water and salt flows into and out of the coal supply system was in progress and therefore not available at the time of this study, so a high level assessment of the water and salt flows was initiated with data supplied by Sasol Mining. This was augmented with published data, data available from other members of the complex and other researchers. The site was in the process of permit application for the NWA and not all the Section 21 activities had been defined. A balance has been obtained on the water and salt flows and physical layout of the operations as determined from the research data. A salt balance set of measurements was not available from the site, so a balance has been prepared in Table 4. This is based on all the data available from the mine and previous studies and includes the conditions for evaporation and coal processing and coal and waste transport at the site.

The sources of water are the Sasol Mining collieries in the Waterval and Leeuspruit catchments. These are Twistdraai, Bosjesspruit, Middelbult, and Brandspruit.

An estimate of the amount of salts produced over the life cycle of mine water can be deduced from the “Balance” column of Table 4. The inflow of fissure water can be found under the ‘Source’ column Table 4. Mine water flow is about 50 Mℓ/d with a salt load about 43 t/d. The conversion of fissure water into mine water by the sulphide oxidation in the underground mine can be found under the ‘Source’ column and is calculated from the ‘balance’ column for the TDS daily flow at around 214 tonnes per day. The total of the mass flow of salts per day through the mine is around 250 t/d. This salt balance is allocated:

- Synfuels gasifiers and combustors plant receive 114 t/d. It is expected that salts are trapped in scrubbing liquids and air pollution equipment, and ash. Final destination is Synfuel ash-water system.
- Synfuels mine water desalination plant receives 49 t/d. The brines which are co-disposed with ash into the ash brine disposal system.
- Sasol Mining coal discards land fill site receives 47 t/d in the fines slurry water.
- The Sasol Mining Coal export mass flow 48 t/d.

This water and salt balance provides for a transfer of salts from the colliery to the Sasol Synfuels disposal sites around 160 tonnes per day.

5.1.1 Long term storage

A set of four surface dams provide temporary storage, however these do not accumulate material in the long term and constitute a static inventory. Discarded coal fines are slurried with dam water and stockpiled, which constitutes an accumulating inventory. Storage of saline water in the four surface dams is summarized in Table 2. The storage in the closed mining compartments is summarized in Table 3. The accumulation of mineral salts produced by the evaporation of mine water for slurry transport of the fines to the Coal Discard Stockpile is provided in the column labelled “storage” in Table 4. At daily flows of 260 tonnes per day of salts on the site, approximately 50 tonnes per day are stored in the Fines and discard land fill site.

On a day to day basis the underground inventory is essentially a static inventory in which mine water is managed by a pumping system. In the long run, the accumulation is approximated by rate of space available for mine water storage that is provided by the rate of removal of coal. This quantity is not known for the case study area. The underground inventory at March 2009 was therefore around 483 000 tonnes of salts.

Table 2: Mine water and the main TDS ions in the Sasol Mining surface dams for 2008-9

		Dam F	Dam V	Dam 11	Quarry dam	Total
Mine Water	Mℓ	2 727	626	178	364	3 895
TDS	T	15 212	3 454	558	1 858	21 081
Ca	T	809	188	16	113	1 127
Mg	T	478	121	11	81	691
Na	T	3 350	706	169	355	4 580
Cl	T	690	147	35	59	931
SO_4	T	8 719	1 978	282	1 041	12 020

Table 3: Mine water and salts stored underground at Sasol Mining in 2008-9

Colliery	Volume	TDS	
	Mℓ	mg/ℓ	tonnes
Bosjesspruit	10 923	5 329	58 213
Twistdraai	45 562	3 531	160 879
Middelbult	19 655	2 749	54 023
Brandspruit	32 198	6 531	210 274
Total	108 338		483 389

Table 4: Summary of Water and aqueous salt flows for Sasol Mining 2008/9

	INFLOW	OUTFLOW									STORAGE	BALANCE
	Fissure Water	MW to SSF	CW to Export Coal	CW Gasifier	CW Steam generation	Evaporation SSFstockpiles	Evaporation MW dams	Evaporation Coal Discard dam	Evaporation Twistdraai SP	Evaporation Coal processing	Coal Discard Landfill	Input - Output
Flow (Ml/d)	50.6	9.0	2.17	7.40	3.5	10.4	2.28	8.84	6.73	0.29	0.0	0.0
TDS (t/d)	43.0	48.7	47.9	39.6	74.3						46.7	-214.1
Ca (t/d)	3.8	2.6	2.6	2.1	4.0						2.5	-10.0
Mg (t/d)	3.2	1.6	0.38	1.3	2.4						1.5	-4.0
Na (t/d)	3.2	10.6	2.49	8.6	16.1						10.1	-44.8
Cl (t/d)	2.3	2.2	0.51	1.7	3.3						2.1	-7.5
F (t/d)	0.023	0.016	0.004	0.013	0.024						0.0	-0.05
SO4 (t/d)	5.8	27.8	6.53	22.6	42						26.6	-120.1
TDS (mg/l)	850	5 412	22 090	11 977	11 977							
pH	8.3	7.8										

Source	water (Ml/d)	salts (t/d)	Destination	water (Ml/d)	salts (t/d)
Fissure Water	50.6	43	evaporation	29	
Colliery		214	combustor/gasifier	11	114
			SSF desalination	9	49
			Coal Discard Landfill	0	47
			Export Coal	2	48
total	**51**	**257**	**total**	**51**	**257**

Traceability	SASOL MINING, *Twistdraai simplified process flow diagram.*
	HODGSON, F.D.I. and KRANTZ, R.M., 1998. *Groundwater quality deterioration in the Olifants River catchment above Loskop Dam,* University of Orange Free State.
	NUSSEY, G., MAFANYA, T. and BOTHA, B., 2009. *Sasol Mining Information.* WRCK5/1833/3. Secunda: .
	ROUX, D.T., 1999. Waste Water recycling experience at the Sasol Synthetic Fuels plant. *The South African Process Engineer,* April.
Note 1:	pH in Coal Water (CW) flows are assumed to be constant, ie, there is no formation of Acid Rock Water in the storage areas
Note 2:	CW concentrations are assumed to increase only as the result of evaporation and dust suppression flow to maintain constant moisture ; areas taken from 2003 satllite images
Note 3:	Recovery of clean fissure water is not possible due to mining operations and structures; fissure water is mixed with mine water
Note 4:	TDS calculations are analyses of mine water in above-ground storage dams. Ie, TDS calculations exclude any formation of salts in fines dams, and coal washing and effluent run-off dams
Note 5:	TDS calculation includes bicarbonate based on the Total Alkalinity measurement at pH 4.4
Note 6:	Evaporation rates for coal stockpiles, land fill, and storage dams are derived from evaporation data at Harmony Gold, New Denmark, Eskom, standards, and publications,eg, for Coal Evaporation rates for coal stockpiles are estimated at 1.07E-05 Ml/d/m^2 which is about 2.8 times that of open water evaporation reported by Harmony Gold.
Note 7:	Water in Ventilation air flows excluded from water balance: this will increase the FW flow balance calculation
Note 8:	Mine Water flows to evaporation areas and coal stockpiles are based on an evaporation rate
Note 9:	Sasol TDS calculation methods are not standardized or the DWA method; the Sasol Mining TDS values are used for all the salt flows and derived water flows.

5.2 Sasol Synthetic Fuels

The main source of water is raw water supplied from the Grootdraai dam at 238 Mℓ/d via a canal and pipeline to the Bosjesspruit dam which is located outside the site boundaries. Mine water at 9 Mℓ/d makes up about 4% of the daily water flow. The Sasol Synfuels site has been established with waste disposal and storage facilities on site and these account for the almost all of the salts resulting from operations. The main outflow of the water is 251 Mℓ/d by evaporation which is not a discharge activity under the NWA and for that reason is not considered a waste and does not require a permit for release. A summary of the daily water and salt flows is contained in Table 8 and Table 9.

A 6 Mℓ/d continuous discharge to the Bosjesspruit is a low salinity effluent originating from cooling tower blow down. In addition there is an intermittent discharge to the Klipspruit from rain water runoff holding tanks. Evaporation to atmosphere takes place in the cooling towers, ash disposal sites, and waste water storage dams, as well as in the combustion and gasification chambers. Evaporation and likely droplet entrainment take place in the cooling towers. Assisted evaporation takes place with the organic waste water treatment works via mechanical aeration.

Sasol Synfuels has two chemical processes which destroy or create water. Water is an ingredient in the production of syngas, and water is a by-product from the Synfuel process from the reaction of carbon monoxide with methane.

The production of syngas may produce additional aqueous salts from coal that would not be produced as either a mineral salt in ash or as an aqueous salt in the ash-water storage and disposal system. F, Cl, and S gases are produced in the high temperature gasification of coal. The halides minerals have the lowest boiling points of the minerals and as the hot gas quench for is enriched in these salts, it is likely that they are transported as gas rather than coal ash. The source of these halides can be either salts in coal water or minerals in the coal gasification process. Sulphide gases are a waste product from gasification of coal, and will react with water to produce sulphate salts. Synfuel production employs the Sulfolin process to remove sulphur from the syngas stream from where it is sold as elemental sulphur. A comparatively small sulphate by-product is crystallised as sodium sulphate and sold to the market.

Additional inputs of water to the daily mass balance include coal water, slurry water with fine coal, and rain water. Sasol estimates coal water at 8.25% the mass of the coal. At 110 kt/d of coal the coal water volume is estimated to be about 10 Mℓ/d at Sasol Synfuels. Coal is being replaced by gas but is a small fraction and is not included in this mass balance of water and salts. However there are cleaner production benefits from gas. Specific water usage is increased due to the larger percentage mass of H in gas compared to coal. Salts in coal water are reduced.

Rain water is treated as a boundary flow. Salts in storm water are an internal flow and not included in the mass balance for salts.

The design intent for desalination has been published by Sasol Synfuels in 1999 (Roux, 1999; Roux, 2000) and in 2007 (Grant, 2007). Changes to the plant since 2000 include a Synfuels production capacity expansion, and a salt and water pinch technology cooling water recovery from cooling tower waste water. This latter project is called Project Landlord and the result is a reduction in effluent discharge to the Bosjesspruit (Grant, 2007). Other changes to the design intent of the desalination systems have not been published but have been made available to this study (Gilliland, 2008). These indicate operational changes to the desalination system but no change in the salt storage system.

Results from research on the reactions of coal and brine, indicate salt storage capacity for fine ash compared to coarse ash (Mahlaba et al., 2008). Another area of research is salt mineralization by exposure to CO_2 in the atmosphere. The findings are not yet ready for publication. The design intent on destinations of the salts is:

- Accumulation system 350 tonnes per day.
- Discharge to the surface water system 2%; at 9 tonnes per day
- Recovery of salts at industrial grade as feedstock on site up to 6%; at 15 tonnes per day.

5.2.1 Storage

The information concerning Sasol Synfuel ash-brine storage system can be divided into two major categories: the solid ash and the liquid brine. More detailed data are available for the brine streams than the ash, as the ash mineralogy is complex. The singly charged ions (Na, K, and Cl) have the highest solubility and also represent the greatest environmental risk because of their mobility in natural systems. F is precipitated as CaF_2 in the ash system at Synfuels.

Coal ash has been found to contain a significant proportion of salts which under appropriate conditions could dissolve in the brine. It is also possible that salts in the brine might precipitate onto the ash in particular the multiply charged ions (Ca, Mg, SO_4, and CO_3). It is therefore desirable that these exchangeable salts in the ash should be considered as part of the salts inventory for the process. In principle all salts are exchangeable; however in practice the exchangeability is dependent upon the solubility limits in complex mixtures and diffusion rates from low to high concentration. This is part of the recently reported research on ash salt absorption processes in the ash brine disposal system (Mahlaba et al., 2008). However, despite expected lower mobility and lower net solubility, the quantities of these coal ash minerals are much greater than aqueous salts. So much larger salt loads are possible. For these reasons it is useful to consider them in the salt balance, but separately from mine water salts.

There is equilibrium between the salts stored in solution and the salts stored in ash. The available data is summarized under the heading 'Accumulation = Inflow – Outflow' in Table 8. The amount of water flowing into the solid ash stream is 7 Mℓ/d. The amount of water entering the aqueous storage system is determined by difference, i.e. 19.3 Mℓ/d. The salt flow for 2008/9 is estimated to be less than 349 t/d. The long term water balance for the site (SASOL, 2010) over the past decade does not accommodate this as a long term flow. It is likely therefore that this flow is the difference between the design flow intent and the actual flows in the inflow and outflow columns. The column headed 'Ash water & brines' provides an indication of ranges of salt concentrations. The most recent ash water concentration is about 6792 mg/ℓ and the brine concentrations are in the range 1% to 15%.

The daily contribution of mineral salts from ash is estimated from the formula used to estimate partitioning between the mineral salts and the brines. This accumulation of the mineral salts per day is around 2 011 t/d (as illustrated in Table 7).

An indication of the relative contributions by the main sources of aqueous salts is provided in Table 5. Salts from the mines and treatment chemicals are about 130 t/d and raw water and gasification salts are about 89 t/d. An indication of the quantities of aqueous salt storage inventory is provided in Table 6. Partitioning of contributions from the ash to the clear ash water and brines is an area for research publications.

The daily contribution of inventory of aqueous salts is estimated at 379 tonnes TDS. The long term inventory of salts dissolved in the main waste water dams has been estimated using typical TDS concentrations (Roux, 2010) and dam volumes provided for 2005 and 2006 (SASOL, 2010). This aqueous inventory is shown inTable 6.

Table 5: Relative contributions by the main sources of dissolved salts in the Sasol Synfuels process water systems

Source		MW	RW and Gasification	Treatment Chemicals	Total
Contribution to daily salt flows	%	38%	26%	36%	
	t/d	134	89	126	349

Table 6: Aqueous salt inventory at Sasol Synfuels

Dam system	Ml	TDS (g/ℓ)	TDS (t)
Salty water	1 975	31	60 336
Process Water	9 300	3	24 723
Ash Water	6 150	12	76 721
Total	**17 425**	**46**	**161 780**

In the absence of data on the exchange between aqueous salts and mineral salts estimates of the ash contribution to the overall balance have been made using a model 'recipe' of Sasol Synfuels fly-ash that has been used to research and predict ash-brine interactions. The ash is modelled as approximately 93% inert minerals and 7% partially soluble salts. The main components of the partially soluble fraction are CaO, $CaCO_3$, $CaSO_4$ and MgO. At the estimated rate of 28 000 t/d of ash produced per day, the upper estimate to rates of accumulation are shown in Table 3.

Table 7: Model estimated rate of accumulation of mineral salts contributed by ash from Sasol Synfuels. Main components of the water soluble salts are CaO, $CaCO_3$, $CaSO_4$ and MgO

	Accumulation (t/d)
Ash	28 728
Sum of main water soluble components	2 011
Ca	803
Mg	291
SO_4	220

What is clear is that these estimations indicate that solid flows are an order of magnitude greater than those for the dissolved species. It is likely that the Mg and SO_4 remain in the solid phase under the conditions of the ash-brine system, and they may even precipitate from solution phase. The situation with Ca is less clear, further research is required.

Table 8: Summary of Water and aqueous salt flows determined from Waste Water Treatment System Design Intent and measurements Sasol Synfuels 2008/9

	INFLOW						OUTFLOW							Accumulation = Inflow-Outflow			
	RW	MW	CW	Rain W	Treat. Chem.	Gasifier salts	CTW Evap.	WW Dam, Ash evap.	Disch. to SW	Steam losses	CW evap.	Water in Product	Crystalz. Salts	Ash	Ash Water (& Brines)	Inflow - outflow	% of inflow
Water (ℓ/d)	238	9.0	10.9	18.7	0.0		166	31.8	6	15	3	35.2	0.0	7		19.3	7.0%
TDS (t/d)	47	49	94		135	49			9				15.0			349.4	93.6%
TDS (t/a)									3 219								
SS (t/d)	3.4	130	0.9		0	0			0.73							133.7	99.5%
pH	7.9	7.8															
Ca (t/d)	3.7	2.6	4.6		25	0										36.4	100%
Mg (t/d)	2.7	1.6	3.1		10	0										17.5	100%
Na (t/d)	3.6	11	20		23	2			0.8				4.8			53.4	91%
F (t/d)	0.04	0.2	0.3		0.00	7			0.02							7.0	99.7%
Cl (t/d)	2.7	2.2	3.3		18	8			0.7				1.7			31.8	93%
SO4 (t/d)	8.8	27.8	48		35	33			0.7				10.2			141.9	93%
TDS (mg/ℓ)	196	5 412	11 977		-	1 788	5 000		455						6 792		
TDS Max%															(15%)		
TDS Min%															(1%)		

Traceability

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Note1: Gasifier salts are determined from the mass flow of the salts in the Stripped Gas Liquor

Note 2: pH in CW flows is assumed to be constant, i.e., there is no formation of Acid Rock Water in the storage areas

Note 3: CW concentration are assumed to increase only as the result of concentration due to evaporation of dust suppression flow

Note 4: Pumping of clean fissure water is not possible due to mining operations and structures (G Nussey 20100830); fissure water is mixed with mine water

Note 5: Calculation excludes formation of salts in fines dam, and washing effluent dams

Note 6: Calculation includes alkalinity calculation for TDS

Note 7: Assumption Export coal: washed with mine water once thereafter dust suppression spraying at evaporation rate for coal stock pile\

Note 8: Evaporation rate for coal stockpile calculated for mass balance of water at Anglo Coal

Note 9: Overall water balance excludes other water sources, e.g., excluding rain fall on dams coal stockpiles, etc. Actual MW flows will be lower by the rain fall on stockpiles.

Note 10: Calculation of F in gasification quench water appears to be too high for CW and is too high for F in coal compared to Cl in CW and S in coal.

Note 11: Calculation of Water consumed in Sasol Synfuel product was provided in a draft report to Sasol Synfuels in Sept. 2009

Table 9: Sources and destinations of water and aqueous salts at Sasol Synfuels site

Source		Destination		
INFLOW	**Salts (t/d)**	**Outflow/Accumulation**	**water (Ml/d)**	**salts (t/d)**
RW	47	Disch. to SW	6	8.8
MW	49	Evaporation	201	0
CW	94	Steam losses	15	0
Rain W		Water in Product	35	0
Treat. Chem.	135	Crystalz. Salts	0	15
Gasifier salts	49	Accumulation/unaccounted	19	349
Total	373	**Total**	277	373
			water (Ml/d)	**salts (t/d)**
		Surface water system	6	9
		Evaporation	251	0
		Product		15
		Accumulated/unaccounted	19	349
		Total	**277**	**373**

5.3 New Denmark Mine

The physical boundaries of the New Denmark Mine Sasol Synfuels site have been discussed by the study team and agreed with the representatives of Anglo Coal New Denmark Colliery, Eskom Tutuka, and DWA. On the North and West the lease bounds the Sasol Mining lease of the Middelbult Mine and on the South East the Eskom Tutuka Power Station (see Figure 3). The underground workings are drained by the Waterval, the Leeuspruit, and the Blesbokspruit tributary. Data for flows was supplied by New Denmark, DWA and Eskom (Thema, 2009; Janse van Noordwyk, 2009b; Hanekom, 2010; Janse van Noordwyk, 2009a; DWA, 2009c; DWA, 2009a).

New Denmark supplies about 7 Mt/a coal to Tutuka power station and discharges about 11 Mℓ/d of mine water to the Tutuka desalination works. New Denmark receives 2.8 Mℓ/d of potable water which in the mass flow balance is allocated mainly underground for the underground coal face mining equipment. The mine was initially intended to supply between 10 and 14 Mt/a, but production is between 4.5 and 4.9 Mt/a (Mining Weekly, 2007). Although Tutuka is designed for 3.6 GW power output, normal operations are at a load factor of 65%. For the survey period the production average is 59 GWh/d, (Eskom, 2010) with a coal consumption rate of around 11 Mt/a. The shortfall on coal demand for Tutuka is made up by contract coal suppliers who truck in the coal to the Eskom Stockpile from where it is transported on conveyor belt to the power station.

Mine water discharge from the mine to the Eskom power station is via a series of small dams and one large dam named Stockpile Dam. The flows are summarized in Table 13. The mine water for the dam is also used for dust suppression. Flows from the mine to the stockpile dam have been provided by the mine. Flows from the stockpile dam to the power station have been provided by Eskom. The mine advised that there are no Section 21 discharges of mine water to the Leeuspruit catchment. The mine does have a domestic waste water works but these are excluded from the salt inventory because the salt release rates are low.

The life cycle of the mine water commences with the inflow of ground water and potable water into the mine working area. Borehole water is taken to be the saline composition of ground water (DWA, 2009b). The composition of mine water at New Denmark is taken from a typical analysis obtained during the study. (Anglo-Coal, 2009) and is shown in Table 10. The life cycle of the mine water ends with the disposal of 90% of the salts on the Eskom site, and a return of 10% to one compartment underground. The main source of salt is the reaction of ground water with the mine minerals and the rate of salt production is 73 t/d. The life cycle includes the recycling of mine water and the co-disposal of brine from Eskom with mine water flooding in compartment 321.

The approach to integrated eco-efficiency is demonstrated by the incremental reduction in demand for raw water by the use of mine water. The approach to integrated eco-efficiency is demonstrated by the mixing of brine with underground mine water as an alternative to the co-disposal of brine with ash. These eco-efficiency projects are specified by the DWA water use permits to the power station and New Denmark colliery. The economic and environmental sustainability of the salt storage methods are however not proven and are subject to a WRC research project on underground brine storage at New Denmark. The long term holding capacity of the ash brine co-disposal system is the subject of Eskom and Sasol research collaboration.

Table 10: Mine water composition used for the New Denmark underground mine water calculations

Component of water quality	Concentration (mg/l)
TDS	5017
pH	7.6
Na	1452
Mg	77
SO_4	1270
Cl	1550
Ca	205
Malk	367

5.3.1 Above Ground Storage inventory

The stockyard dam through which the mine water is transferred to the power station is increased in concentration of TDS due to evaporation over the surface of the dam. The quantities of the main aqueous salts are provided in Table 11. The stockyard dam is also supported by a small toe dam which prevents run-off from the stockpile into the stockyard dam, but which is not included in the inventory.

Table 11: Salts stored in the New Denmark coal stock pile dam

Stockyard dam	
Water (Ml)	623
TDS (t)	3128
Ca (t)	145
Mg (t)	249
Na (t)	889
Cl (t)	620
SO4 (t)	1215

The coal stockpile stored on New Denmark site is sprayed with mine water to suppress dust formation. This system can be used to balance variable ground water flows which change with rainfall, and the relatively steady flows of mine water and coal water to Eskom. The area and evaporation rate of the coal stockpile allows for the mine to meet its permit of 18 Mℓ/d pumping from the mine.

The coal stockpile is too large for normal safety margins and the daily mass flow calculation has a component of storage on the site. This is shown in column Disposal/Storage. The daily coal water salt flow is therefore based on the normal daily consumption by the power station.

5.3.2 Underground Storage

New Denmark colliery stores mine water in flooded compartments, in underground dams and stores a mixture of brine and mine water on a special arrangement with DWA, and Eskom (DWA, 2009c). The brine is the effluent from the reverse osmosis desalination system at ESKOM. It is disposed into Compartment 321. Table 11 shows the average daily flow for 2008/9 of 0.66 Mℓ/d at an estimated 10 t/d TDS. Details on the disposal methodology are being researched with WRC. The method in April 2009 includes mixing of brine with lime, and co-disposing with ground water and mine water flows as part of the process of flooding the compartment. The ratio of brine inflow to other inflows is estimated at 1 to 5. A summary of the underground inventory is in Table 12.

Table 12: Stored aqueous salts underground at New Denmark colliery at 2008/9

			Volume	TDS	
			Ml	mg/l	tonnes
Underground Flooded Compartments			12 159	4 301	52 300
Underground pumping dams			247	5 017	1 240
Brine and Mine Water storage			3 000	5 017	15 052

Table 13: Summary of water and aqueous salt flows for Anglo-Coal New Denmark colliery 2008/9

	INFLOW			OUTFLOW				Disposal/Storage		Balance
	Fissure Water and Potable water	Brine	CW from suppliers	MW to Eskom Tutuka	CW to Eskom Tutuka	Stockpile Evap.	MW dams Evap.	Disposal Compartment 321	Storage Strategic coal stockpile	Inflow-Outflow-storage
Flow (Ml/d)	17	0.66	1.1	11.2	1.8	4.1	0.96	0.66		0.00
TDS (t/d)	13	10	5.3	60	14			10	17.2	-72.9
pH	8.3	6.9						6.9		8.3
Ca (t/d)	0.6	0.1	0.2	2.8	0.6			0.1	0.8	-3.4
Mg (t/d)	1.0	0.1	0.2	4.8	0.7			0.1	1.4	-5.7
Na (t/d)	2.1	3	1.0	17	3.2			3	1.4	-18.7
Cl (t/d)	3.1	0.3	0.2	12	1.2			0.3	3.4	-13.4
SO4 (t/d)	4.7	5	2.5	24	6			5	6.7	-29.2
TDS (mg/l)	718	15 908		5 335	7 702			15 908		

Source	**water (Ml/d)**	**salts (t/d)**	**Destination**	**water (Ml/d)**	**salts (t/d)**
Fissure Water and Potable water	17.0	12.7	MW to Eskom Tutuka	11.2	60
Eskom Desalination Plant	0.7	10	CW to Eskom Tutuka	1.8	14
			Strategic coal stockpile		17
Mine workings underground		72.9	Evaporation	5.1	
CW on contractors coal supplies	1.1	5.3	Storage underground	0.7	10
total	**19**	**101**	**total**	**19**	**101**

Traceability	DWA, 2009-10-22 13:26, 2009b-last update, list of boreholes only for region C. [Homepage of DWA], [Online]. Available: http://www.dwa.gov.za/iwqs/wms/data/C_reg_WMS_boreh.htm [December/8, 2010]. DWA, 2009a. Brine Report April 2009: NWA Directive New Denmark Mine 16/2/7/c114/c074, April 2009. Pretoria: DWA. HANEKOM, D. 2010. *Tutuka Power Station Theoretical Water Balance.* Johannesburg: ESKOM. JANSE VAN NORDWYK, J. 2009. *Interview ESKOM Tutuka Power Station March 17 2009.* THEMA, G. 2009. *Mass flows of salt and water at New Denmark Colliery* .
Note 1:	Fissure Watter (FW) composition has been taken from DWA Borehole water analyses at Charl Cilliers and Secunda residential area.
Note 2:	Mine Water is used for dust suppression on stockpiles and disposal sites and is disposed when there is an excess water in the system.
Note 3:	pH in Coal Water (CW) flows are assumed to be constant, ie, there is no formation of Acid Rock Water in the storage areas
Note 4:	CW concentration are assumed to increase only as the result of concentration due to evaporation and dust suppression spraying
Note 5:	Salt formation in the Stockyard Dam from reactions with coal fines and water is included in the total salt load measurement but is excluded as a source.
Note 6:	Salts content of RW and Mine Water (MW) flows inlcudes alkalinity calculation for TDS
Note 7:	Salt formation is assumed to take place only underground in the working compartments
Note 8:	Coal water is taken as 6% by weight by Eskom at the entrance to the boiler although the limits on moisture supplied to the stock pile may be higher.
Note 9:	Potable Water (PW) is supplied to the colliery by Eskom and is used mainly for cutting water. This flow at about 2.8 Ml/d is added to the FW inflow.
Note 10;	Evaporation rate for coal stockpile calculated from the balance of the water flows over the stockyard stockpile. This agrees with the permit max flow.

5.4 Tutuka Power Station

The main inflow to Tutuka is 97 Mℓ/d of raw water from the Grootdraai Dam. Raw water is converted to potable water via a clarifier filter (see Figure 7). Potable water is supplied to New Denmark Colliery and public users. Mine water from the colliery is desalinated. A summary of the water flows and associated salt flows is shown in Figure 6 and Table 15. Coal consumption is 30kt/d of which 12.3kt/d is supplied by New Denmark.

A zero effluent licence was initiated in 1984. The waste salts were collected and stored on site. In 2008-9 brine is mixed with ash and co-disposed on the disposal site. At the time of the governance survey in 2009, the NWA (1998) water usage application was in preparation. The 1956 Water Act permit (DWA, 1994) for industrial waste water use from power generation was in operation. Total allowance was 129 Mℓ/d and did required use of mine water to reduce raw water demand. The 2009 permitted water use has been is 97 Mℓ/d.

Tutuka is a standby power station in the Eskom power generation network, i.e. it has a nominal 65% load factor on its theoretical maximum output of 3.6 GW. This determines the amount of water consumed for cooling. The theoretical optimum requirement for evaporative cooling is 1.55 ℓ/kWh. Specific water usage for 2008/9 was 1.9 ℓ/kWh. This is higher than the theoretical minimum and other power stations in the area, for several reasons. These include keeping boilers on standby, where unused energy is evaporated as water. Another reason proposed by Eskom is a faulty return leakage valve on the water supply system. Savings by the use of mine water in 2008/9 amounted to 0.18 Mℓ/kWh. This reduces the raw water use to 1.72 ℓ/kWh.

The reduction in raw water to 32 Mℓ/d has also been achieved by water efficiency.

Eskom Tutuka has provided four sets of mass salt and water flow data. These are the permit quantities design and actual as reported (DWA, 2009a), the raw water report for 2008/9 (Janse van Nordwyk, 2009b), the theoretical water balance with a water balance diagram (Hanekom, 2010b), and the consumption rate of treatment chemicals and the brine sink limitations for dust suppression, bottoms ash injection and fly ash pasting (Janse van Nordwyk, 2009).

A summary of the design intent of the processes as relate to water flows at the power station has been provided by Eskom (Hanekom, 2010) and is shown in Figure 6. All the mass flow data has been combined into a process flow diagram in Figure 7 which shows the flow of the aqueous salts through the power station.

The first step in desalination is the removal of bicarbonate and precipitation of multiply charged ions by heating and addition of lime. Spiral reverse osmosis produces two grades of desalinated water: boiler feed water and cooling water. The brine is mixed with ash or discharged underground at New Denmark compartment 321. Other desalination techniques include vacuum evaporation for recovery of cooling water from brine, and ion exchange for production of ultra-pure deionised water for the high temperature steam production.

The main salt flows are to Eskom. Mine water (11 Mℓ/d with 62 t/d) and coal water (6% of coal mass with 14 t/d). These are supplied from the coal stockpile and stockyard dam. Two grades of desalinated water are produced from the 11 Mℓ/d of mine water by reverse osmosis. The higher grade effluent is used for boiler feed water, and the lower grade is fed to the cooling water system. The brine effluent is either co-disposed with ash at the ash disposal site, or disposed underground at New Denmark Mine. The return flow of brine to New Denmark is 0.67 Mℓ/d and contains about 10 t/d of salt.

Aqueous salt flows are not measured, but are determined by the difference between the measured inflow of salts in mine water, raw water, and water treatment chemicals. A daily salt flow of 115 t/d passes through the power station. Compartment 321 receives 10 t/d. The ash-brine co-disposal site receives 105 t/d. No discharge of industrial waste water is made from the Tutuka site.

5.5 Storage

Salts in fly ash can be estimated using a model ash recipe of Tutuka fly-ash. This is very similar to the recipe for Sasol Synfuels ash, with slightly different proportions of mineral phases as is shown in Table 14 for the major constituents of ash based on the estimated ash production rate of 9000 t/d.

Table 14: Estimated rate of accumulation of salts contributed by ash at Tutuka; Major salt components are CaO, $CaCO_3$, $CaSO_4$ and MgO

	Accumulation (t/d)
Ash	9000
Major components of water soluble ash	636
Ca	261
Mg	44
SO_4	231

The rates of accumulation of the mineral salts are of the order of 10 times greater than the aqueous salts. The data, however, did not allow a calculation of material balance discrepancies which might indicate whether a net precipitation or dissolution of salts takes place at the time of storage in the ash-brine co-disposal site.

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Table 15: Water and aqueous salt flows at Tutuka Power Station 2008

	Inflow					Outflow					Storage	
	RW	MW	CW	SW	Treatment chemicals	Cooling	Stack	Site evap.	Evap.	PW	Compart. 321	Ash-Salt
Flow (Ml/d)	96.6	11.2	1.8	0.3	0.0	91.4	1.8	2.4	2.9	3.6	0.8	2.2
TDS (t/d)	19.6	61.8	9.9	0.0	20.3	0.0	0.0	0.0	0.0	-	10.1	101.5
Ca (t/d)	1.8	2.6	0.4	0.0	14.5	0.0	0.0	0.0	0.0	-	4.3	15.0
Mg (t/d)	1.3	4.5	0.7	0.0	0.0	0.0	0.0	0.0	0.0	-	0.1	6.4
Na (t/d)	1.7	16.0	2.6	0.0	0.8	0.0	0.0	0.0	0.0	-	2.6	18.4
Cl (t/d)	1.1	11.2	1.8	0.0	0.0	0.0	0.0	0.0	0.0	-	0.3	13.8
SO4 (t/d)	3.7	21.9	3.5	0.0	0.0	0.0	0.0	0.0	0.0	-	5.0	24.1
TDS (mg/l)	203	5 507	5 285	2 720								15 908

Source	water (Ml/d)	salts (t/d)	Destination	water (Ml/d)	salts (t/d)
Raw Water	96.6	19.6	Evaporation	96.7	0.0
Mine Water	11.2	61.8	Potable water	3.6	-
Coal Water	1.8	9.9	Compart. 321	0.8	10.1
Storm Water	0.3	0.0	unaccounted flow	6.0	
Water Treat.	0.0	20.3	Ash dump	2.2	101.5
total	109.9	111.6	total	109.2	111.6

Traceability

JANSE VAN NOORDWYK, J. 2009. *Raw water report, year 2008/9 Tutuka Power Station.* Tututa: ESKOM Tutuka Power Station, Chemical Services.

JANSE VAN NOORDWYK, J. 2009a. *Chemical consumption for Reverse Osmosis, Mining Water, and Raw Water treatment, year 2008/9 Tutuka Power Station.* Tututa: ESKOM Tutuka Power Station, Chemical Services.

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Note 1: Input data used in the mass balance based in reliability in order of invoiced flows, plant records, and Theoretical flows. Net balance on the inflow minus outflow water calculation is +3.9 Ml/d or +3.6%

Note 2: An average Mine Water (MW) composition for the Highveld Coal field has been used. The value was calculated from the average of 5 mines.

Note 3: Coal Water (CW) is calculated at 6% for Eskom coal. The amount of dust suppression CW used is based on the evaporation rate for the coal. See New Denmark calculations.

Note 4: Stack water outflow is calculated from the CW flow. CW salts and Volatile salts from coal ash are calculated in the Fly Ash flow.

Note 5: Site Evaporation includes evaporation of Potable Water (PW), 50% of the Effluent water to the ash conditioning unit, and evaporation of the CW dam

Note 6: Ash Salt storage is calculated by difference from the other sources of data, as there is no other data available

Note 7: Ash Salt storage excludes salts available in the coal ash. There is no data available. Estimates range from 2% to 7% of the total mass of ash

Note 8: pH in CW flows are assumed to be constant, ie, there is no formation of Acid Rock Water in the coal stockpile

Note 9: CW concentration are assumed to increase only as the result of concentration due to evaporation of dust suppression flow

Note 10: Storm Water SW) concentrations are not available from Eskom, therefore a SW concentration is taken from Sasol Synfuel

Note 11: Calculations exclude evaporation and transport of salts in emissions from Cooling Towers

Note 12: Calculation includes alkalinity calculation for TDS in Raw Water

Note 13: Evaporation rate for coal stockpile calculated for mass balance of water at Anglo Coal

Note 14: Potable Water (PW)

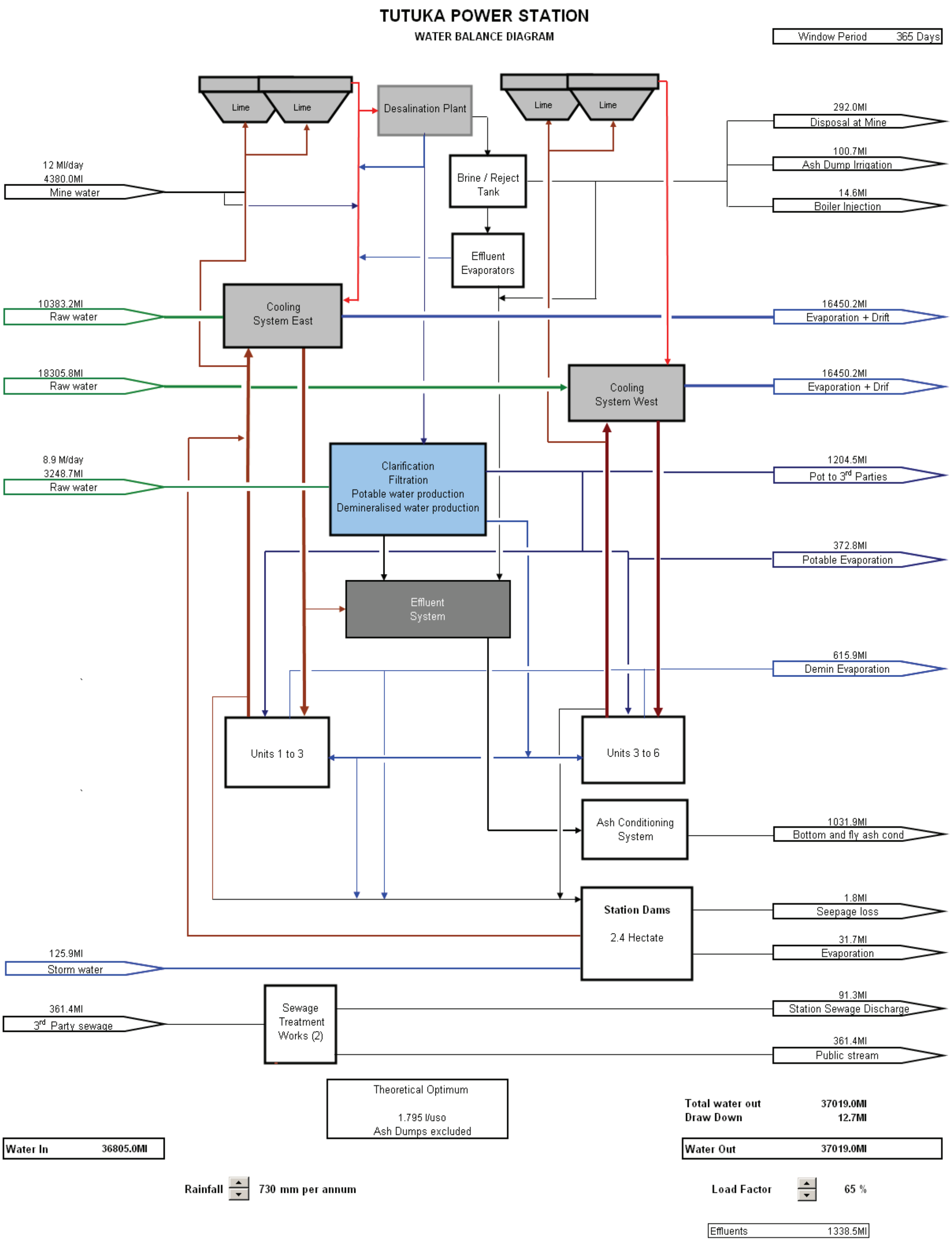
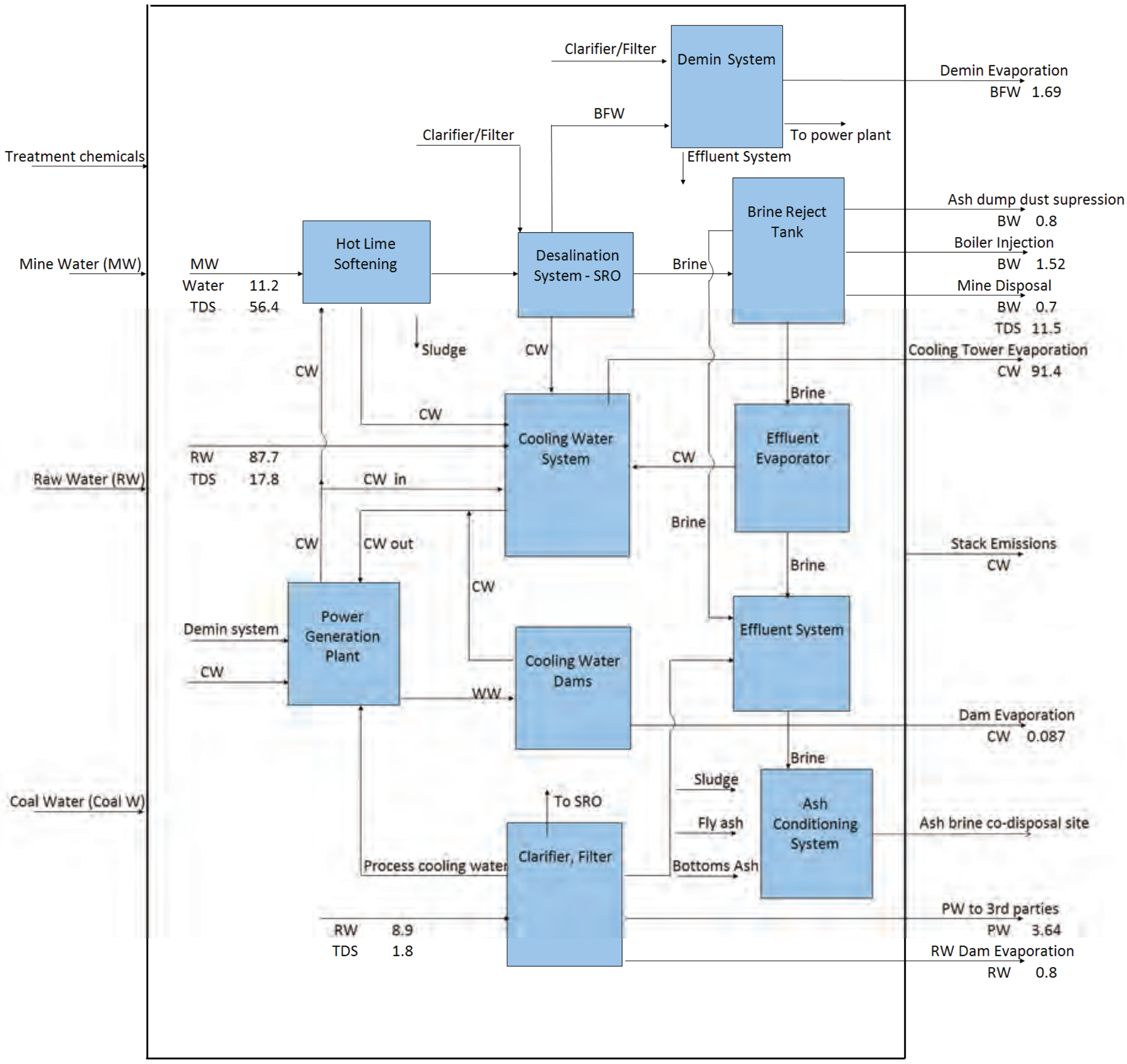


Figure 6: Water balance diagram Tutuka Power Station 2010



Flows	Units
Water	Ml/d
TDS	t/d
Coal	kt/d

BW	Brine Water
BFW	Boiler Feed Water
CW	Cooling Water
Coal W	Coal Water
MW	Mine Water
PW	Process Water
RW	Raw Water
WW	Waste Water

Figure 7: Process Flow Diagram for Tutuka Water and aqueous salt flows 2008-2010

5.6 Evander Gold Mines

Evander Gold obtains most of its working water supply from the shafts mine water flows. Potable water supplied by Rand Water is used mainly for domestic purposes. The mass flow analysis is based on the January flows for 2007 and the January chemical analyses for 2008, so the rain fall is higher than the average. The year water balance for each month in 2007 has been supplied. The results are summarized in Figure 8 and Table 18.

Potable water is supplied by Rand Water; primarily for domestic purposes at a rate of 12 Mℓ/d. A small amount (0.2 Mℓ/d) is used underground. The flow is returned as mine water. Rain water of 60 Mℓ/d is collected in the dams, but its availability for slimes transport is seasonal as the average daily evaporation from the slimes dams is 60 Mℓ/d.

Although the storage of salts in the slimes dams is to some extent similar to the storage of salts in the waste water and brine dams at Sasol Synfuels and Tutuka sites, it has not been possible to perform an analysis similar to the salt ash model in use for Sasol and Eskom. However, there is an important difference, in that the ore has been subjected deliberately to an aggressive leaching environment in the metallurgical extraction process, and is stored in intimate contact with excess water in the slimes dams. It seems reasonable to assume that the process of mobilising salts is mostly completed at the time of storage.

The salt balance over the shaft system, the slimes dams system, and metallurgical plant can be seen in the process flow diagram in Figure 8. Underground working areas produce 18.6 t/d. A summary of the sources and destinations of the salts is provided in Table 18. Salt production in the slimes dams is not measured. There is however some uncertainty in the mass flow balance calculation and a relatively smaller amount (less than 1 t/d) may be formed. Water balance on the slimes dams has uncertainties on the amount of leakage, which is measured in part, and evaporation which is estimated and not measured. These result in an unaccounted TDS flow of 0.9 t/d. This is about 5% of the total salt measurement. So it is concluded that for this data set, the formation of salts in the slimes dams and run-off dams is a minor source relative to the shafts underground.

The storage of salts is indicated by a comparison of the slimes dam run-off flow, which comes from the top of the dam, and the slimes dam leakage, which comes from the bottom of the dam. It is seen in Table 16 that the water leaking from the storage dams is higher in Na, F and Cl than the run-off water. This is consistent with the expectation that the less soluble Ca, Mg, and SO_4 ions would be removed by precipitation during evaporative concentration in the dam, but the more soluble salts will be trapped only by containment of water.

The salt and water flow analysis in Figure 8 shows that the main storage location for the salts is in the large +/- 700 Ha Leeupan evaporation dam. In January 2007 evaporation rates were 14 Mℓ/d and salt storage rates were 31 t/d. It can be seen in column 'Storage/Leeupan' that storage is larger than the amount of salt produced; see column 'Sources of salts' and row 'Underground Work Area' (18.6 t/d). This is due to an internal transfer from the slimes dams and run-off dams (9 t/d) to Leeupan.

A pH of 4.6 occurs in the No 2 shaft and indicates how far along the life cycle of mine water salination reactions that the shaft water was progressed since operations commenced there some time since 1958 when the mine operations commenced. The mine reports however that water is not stored underground as the mines are still in operation. If this is correct then the rate of salination to a pH of 4.6 to occur when the life of the mine water in the mine is of the order of days. Why this would occur in Shaft 2 and not Shafts 7 and 8 mine water discharges is not known, but it is suspected that there is some longer term storage of mine water underground. This can, if required be clarified with the mine at a later stage.

Of interest to the establishment of the rate of salt formation in the mine is the fissure water stream in Shaft 8 which is reported with a TDS of 258 mg/ℓ. This is in contrast to the observations (Hodgson, 1998) that gold mine ground water is expected to be more saline than coal mine ground water. The reasoning is that the water can be released much further underground, and therefore can absorb more dissolved mineral salts as it takes a much longer time to diffuse to that depth. Municipal boreholes analyses were used for ground water salination calculations in the coal mines with an average TDS of 850 mg/ℓ. Other reasons for the low salinity of this ground water include the possibility of an origin much higher than the 2 km underground base of the mine, and the long term desalination of the mineral salts by continuous dissolution of clean water.

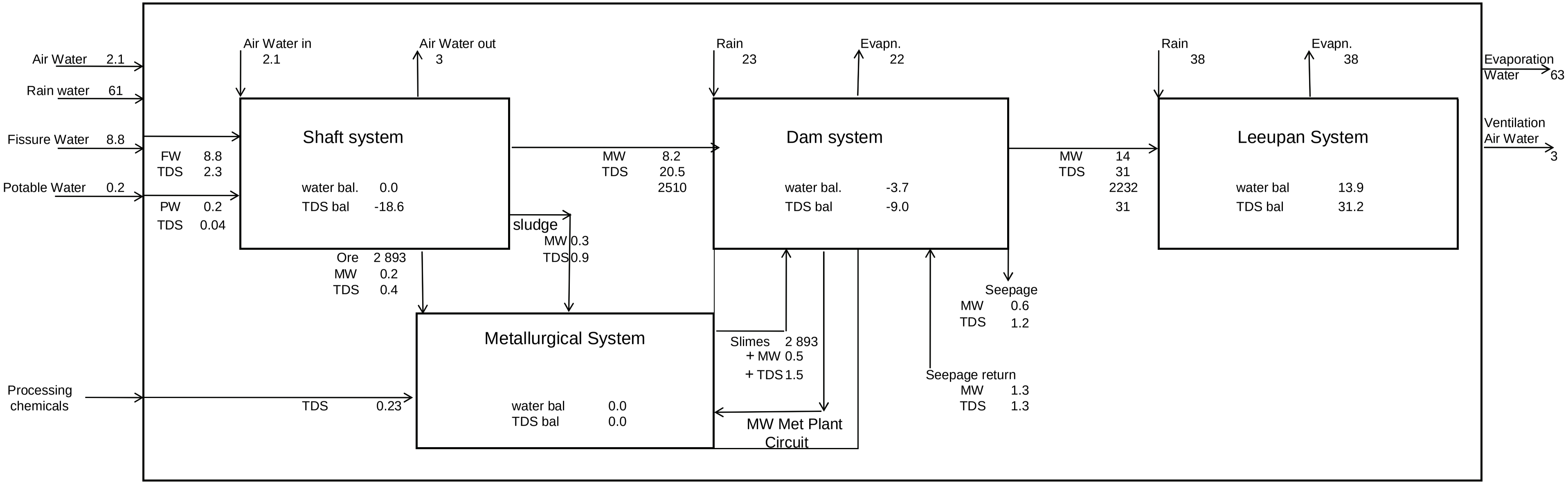
Also of interest is a comparison of the peak recharge rate of 9 Mℓ/d for the gold mine which is considerably lower than the annual average annual of 50 Mℓ/d estimated for these Sasol Collieries, and the 15 Mℓ/d estimated for New Denmark Coal mine. A possible explanation is that the extraction depth is much lower, the gold seams are much narrower, and the mine working areas are much smaller. Evander Gold extracts 3 000 t/d of ore which is considerably less than the coal quantities; 150 000 t/d for Sasol and 8 000 t/d for New Denmark.

Table 16: Slimes Dam run-off and leakage return flow

	Kinross RO dam	Kinross SD leakage return	Leslie SD leakage return
Flow (Ml/d)	5.0	3.2	0.8
TDS (t/d)	23.1	1.5	0.1
Ca mg/l	394	84	81
Mg mg/l	104	25	25
Na mg/l	726	201	230
Cl mg/l	1 348	377	408
SO4 mg/l	1 334	92	135
F mg/l	1.5	1.2	1.3
pH	7.49	8.40	8.27
TDS mg/l	4633	1000	1096

Table 17: Salt content and composition of mine water and fissure water in Shafts, 2, 7 and 8 at Evander Gold

	Winkelhaak Shaft No 2 pumped MW	Kinross Shaft No 7 pumped MW	Kinross Shaft No 8 pumped MW	Kinross Shaft No 8 pumped FW
Flow (Ml/d)	3.2	2.5	2.5	-
TDS (t/d)	7.9	6.0	6.6	-
Ca mg/l	178	101	275	37
Mg mg/l	14	7	10	19
Na mg/l	668	629	738	27
Cl mg/l	1 257	1 101	1 534	27
SO4 mg/l	104	1	336	104
F mg/l	2	3	3	3
pH	4.61	8.43	7.15	7.15
TDS mg/l	2 472	2 400	2 659	258



Flows	Units
Water	Mℓ/d
TDS	t/d
Ore/Slimes	kt/d
water bal.	Mℓ/d
TDS	mg/ℓ
TDS bal	t/d

Rain W	Rain Water
PW	Potable Water
Ore	Rock for gold recovery
Slimes	Ground rock after gold recovery
FW	Fissure Water
Sludge	fine ore recovery from shafts
TDS	Total Dissolved Salts

Note 1: A negative balance on the TDS balance for Shaft operations indicate the production of Mine Water salts in the mine working areas
Note 2: A negative balance on the water and TDS balance of the Dam System is due to the reduction in stored inventory that took place during the month of January 2008

Figure 8: Salt and water flow for Evander Gold

Table 18: Water and Aqueous salt flows Evander Gold January 2008/7

	INFLOW						OUTFLOW			STORAGE		IMBALANCE
	PW	FW	Rain W	Mine Air Ventilation	Return of Slimes Dams leakage	Met. Plant chemicals	Evap. Slimes Dams and Leeu Pan	Mine Air Ventilation	Leakage Slimes Dams	Leeu Pan	Slimes Dams	Inlflow -outlfow - storage
Flow (Ml/d)	0.2	8.8	60.8	2.1	1.3	0.0	60.0	2.4	0.6	13.9	-2.9	-0.8
TDS (t/d)	0.04	2.3			1.3	0.23			0.1	31.2	-7.0	-20.5
Ca (t/d)	0.00	0.3			0.1	0.10			0.0	2.5	-0.1	-1.9
Mg (t/d)	0.00	0.2			0.0	0.00			0.3	0.5	-0.01	-0.6
Na (t/d)	0.00	0.2			0.3	0.04			0.5	5.9	-0.2	-5.5
Cl (t/d)	0.003	0.2			0.6	0.01			0.2	10.9	-0.4	-9.8
SO4 (t/d)	0.008	0.9			0.2	0.00			0.0	6.2	-0.1	-5.0
pH	7.65	7.15			8.40					7.48		
TDS (mg/l)	176	258			1 007				2008	2245	2008	

Source of flows	water (Ml/d)	salts (t/d)	Destination	water (Ml/d)	salts (t/d)
Fissure Water	8.8	2.3	Evaporation	60.0	0.0
Mine Air Ventilation	2.1	0.0	Mine Air Ventilation	2.4	
Potable Water	0.2	0.0	Storage: Leeu Pan	13.9	31.2
Rain Water	60.8	0.0			
Underground work area		18.6	Storage Slimes Dams		
Run off dams storage	2.9	9.0			
Met plant chemicals	0.0	0.2	unaccounted for flows	-2.4	-0.9
SD leakage return	1.3	1.3	SD leakage	0.6	1.2
total	**76.1**	**31.5**	**total**	**76.1**	**31.5**

Traceability
Water analyses supplied by Evander Gold January 2009 prepared by Agri Enviro lab
Evander Gold Mine: Slimes Dams Water Management Diagram and Balance: year to Dec 2007
Evander Gold Mine: Metallurgical Plants Water Management Diagram and Balance: year to Dec
Interview Evander Gold Mine: March 2009.
Evander Gold Mine: Shaft Water Management Diagram and Balance; year to Dec 2007
Evander Gold Mine: Global Water Management Diagram and Balance: year to Dec 2007
Evander Gold Mine: Water Balance Data: Dec 2007
Interview and report Evander Gold Sept, 21 2009

Note 1: Calculations of TDS were standardized to DWA RQS standard records, and measurements for flows.
Note 2: Metered flows are: MW from and Ventilation Air Water in and out of Shafts 2, 7, & 8; Slimes Dams Leakage Return from Leslie and Kinross, Rain fall and dam height at Leeupan, MW from Slimes Dams and Runoff Dams to Leeupan.
Note 3: Rock Water is calculated at 6% . Dust suppression flows are not included. Dam evaporation is based on measured Pan Correction Factors determined from measurements of Leeu Pan; average 0.87
Note 4: Imbalance for salt flow is accounted for in the salt generated in the underground working areas.
Note 5: SAWS rain fall is used for all Rain Water calculations instead of the location specific rain gauge.
Note 6: The average Pan Evaporation Rate Factor is taken as 0.87 from the Leeupan dam level measurements.
Note 7: Interstitial water storage is not taken from the Slimes Dams balances because it is not measured and the calculations used to derive it do not account for uncertainties in site
Note 8: Mine Water evaporation is calculated from the Slimes Dam areas covered with Mine Water. For Example, the whole of Leslie SD receives rain, but a portion receives run off from the Kariba Catchment Dam.
Note 9: Fissure Water (FW) composition is taken from measurement point KM8 in Shaft 8.
Note 10: Slimes Dams inflow and outflows do not balance (see accompanying Process Flow Diagram). This imbalance is allocated to errors in pan factors, and unmeasured leakage, and larger areas for
Note 11: The unaccounted for SD volumes can be due to: the estimation of the evaporation pan factor for a Slimes Dam, unmeasurable leakage, and evaporation from surfaces adjacent to the dam water.
Note 12: Local rain fall data differed from SAWS data by up to 30%
Note 13: Boundaries used for the water flow system differ from those used by the Evander Gold Mine. For this reason the same input data, can give different results. Leakage and return flows from the Slimes Dams and Grootspruit are across the boundary for this study. This assists the allocation of TDS increases in surface water flows covered later in this report.

6 TRENDS IN SURFACE STREAM SALT FLOWS

The objective of establishing integrated cleaner production and integrated eco-efficiency projects is to bring the use of natural resources into line with the environments capacity to supply those resources. This implies the principle of continual improvement in environmental performance with an eventual goal of operating within the carrying capacity of the regional eco-system. All industries in the complex have adopted the principle of continuous environmental improvement (Sasol, 2010; Harmony Gold, 2010; Eskom, 2010; Anglo American, 2010a). Another principle is the principle of economic sustainability. Associated with these two principles is the requirement to minimize of post-closure liabilities, see 1777 Harmony Gold, 2010. So indicators of the long term carrying capacity of the system are required. All the technical design criteria of the disposal sites were approved under permits issued under the 1956 Water Act. The Polluter Pays principle was implemented in the National Environmental Management Act (1998). The water use and integrated waste management conditions were implemented with the new licensing system under the National Water Act (1998). The need for control of the salt storage is also a national priority, but the needs were not quantified in any of the documentation made available to the study.

Surface water flows and salt content was not available from industry at the time of this study. Average monthly water qualities were averaged for period of operation of the industries. DWA provided access to the national water quality data sets of water quality, (DWA, 2009d), laboratory and sampling procedures, flow data, and software suitable for processing the data and estimation salt flows in intermittent stream flows (Walker, 1999). This DWA water quality data bases were verified using ion charge balance, trend analyses, and self-consistency tests, for laboratory inaccuracies and sampling errors (Eaton et al., 2005; AWWA, 1992; USGS, 1989). Two data sets at measurement locations on the border of the complex were acceptable. They are C1H008 on the Waterval River and C1H005 on the Leeuspruit (see Figure 3). The history of each of the flows was evaluated using the life of site record plots that are found on the DWA website, and the history of the sites as indicated by the stakeholders in the region. Five periods of flow and salinity regimes were selected for the 33 years of DWA flow and water quality records.

The FLUX software package was tested and found to be suitable for the data set. Flows were highly variable and on occasion, with much fewer chemical analyses than flow measurements. The Flow Weighted method was the most robust method. The software results were easily verified by a spread sheet calculation. Mass flow rates of salts were calculated using the following equation:

$$W = [tds].\ Q$$

Where

Q = mass flow in m^3/s, calculated from all the stream flow data

q = mass flow in m^3/s, calculated from only the stream flow data for which there was a salt composition measurement

$[tds]$ = concentration of total dissolved salts using the DWAF calculation method reported in mg/ℓ

$W1_{avg}$ = unweighted mass flow calculation of total dissolved salts for that data set sampling period reported as t/a.

$W2_{avg}$ = flow weighted mass flow calculation of total dissolved salts for that data set sampling period reported as t/a.

n_Q = number of stream flow data in the sampling period reported

n_{TDS} = number of salt flow data in the sampling period reported

Two long term monitoring stations provide flow and water quality data for most of the mining and industrial operations. These can be seen in the colour Google map in Figure 4. C1H5 is on the

Leeuspruit below the New Denmark and Bosjesspruit Collieries and a Tutuka power dam. C1H8 is on the Waterval River below the Sasol Mining Collieries, Sasol Synfuels, and Harmony Evander Gold mine and Govan Mbeki Municipality. The possibility of salt contributions by Sasol Mining to the Grootdraai dam are excluded as there is no mining underground any part of the Grootdraai catchment. The possibility of salt release downstream of the Tutuka ash site cannot be excluded because DWA was unable to provide monitoring data.

The long term trends for the Periods of salt flows have been identified using the DWA data set for the region. . The locations of the monitoring points relative to members of the complex are shown above in Figure 3 and Figure 4. Several other monitoring points were evaluated, but found to have too short a history, or an incomplete or inaccurate set of measurements. Errors in analytical methods and error trends were observed in the DWA RQS data set and clarified with the RQS specialists and the data set was adjusted if possible. The long term stability of the RQS laboratory measurements was verified over 35 years to ensure that trends in stream flow were not artefacts of laboratory or sampling procedures. The most stable point in the DWA data set was found to be in Lesotho, and no measurable curve trend could be detected using the accuracy limitations of the least squares method on Excel 2003.

6.1 Flow measurements at C1H005 located on Leeuspruit below New Denmark and Bosjesspruit Colliery underground storage

The C1H005 flow measurement station was established in 1976 six years before the production of coal for Sasol Synfuels and Eskom Tutuka in the years of 1981 and 1982, but 20 years after the establishment of the mining of Gold at Evander Gold. The stream salt flows during this period provide a baseline of 175 mg/ℓ of TDS. This is comparable with other pre industrial stream salinity as can be found from DWA priority measurement stations established over that period. Sample stratification into flow and salinity regimes has been prepared for the purpose of identifying flow periods so that an analysis of the trends in salinity can be identified. Industrial loadings have been calculated by subtracting this baseline value and are shown in Figure 10. The measurement summary and history of the flows are given in Table 19 and Table 20. The trend in TDS is upward (Figure 10) indicating an increase in load with the length of time of the industrial activity. The ratios of the signature for mine water salts have been compared with those prior to the commencement of mining in 1982 and are shown in Figure 9. Increased amounts of Cl and SO_4 are associated with the recent exposure of un-weathered rocks to surface water flows. Increased SO_4 is typically associated with sulphide oxidation from underground mining. Ratios over 0.5 can be correlated with mining or industrial activities.

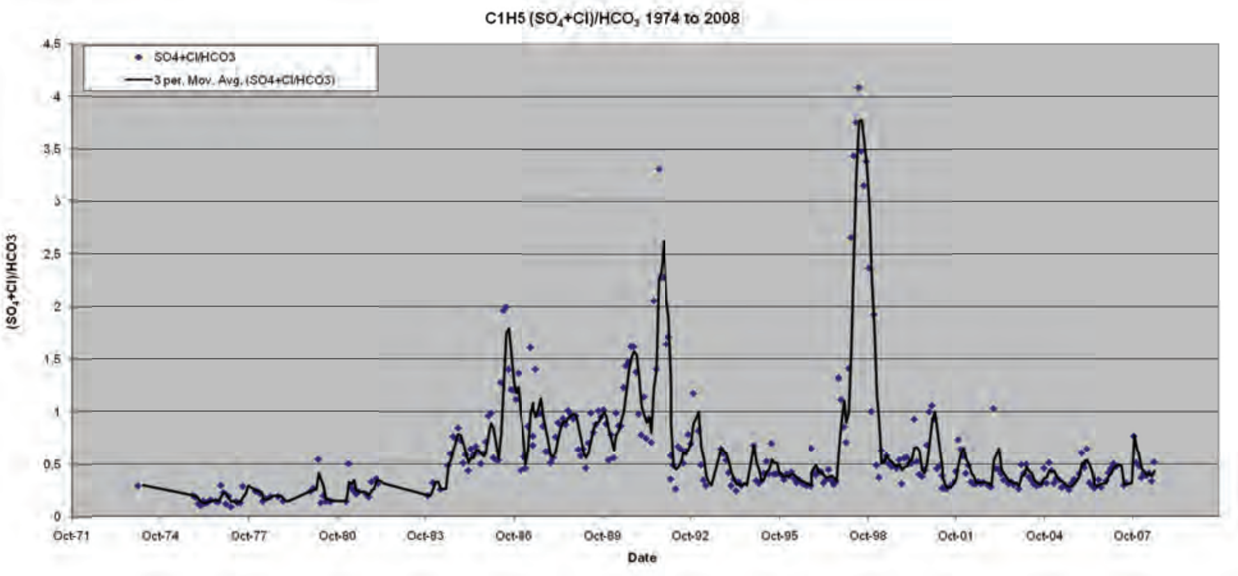


Figure 9: [SO_4+Cl]/HCO_3 1974 to 2008 in Leeuspruit at C1H005 sampling station

The indications are that the origin of the TDS is mine or processing industry salts, with an increasing trend to larger amounts of salt being released from the complex. The baseline estimate with the pre-mining TDS in the Leeuspruit indicates that loads above 5kt/d can be attributed to changes in salt release in the catchment. For the averaging period from 1999 to 2008, it is expected therefore that the industry load is around 7 kt/a, an explanation for the increasing trend has not been available to the study.

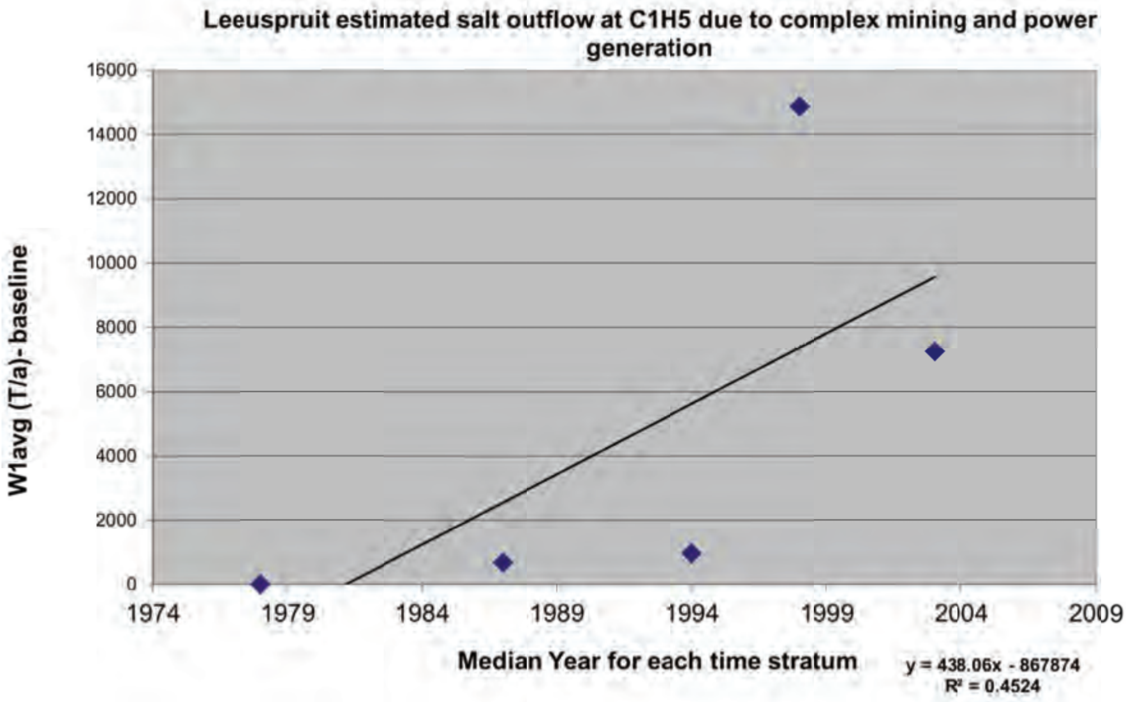


Figure 10: Estimated stream loadings due to mining and power generation in the Leeuspruit stream

Table 19: Statistics for flow measurement at C1H5 on the Leeuspruit between 1974 and 2008

Parameter		Time Stratum					
	Units	**1974-2008**	**1974-1982**	**1983-1991**	**1991-1997**	**1998**	**1999-2008**
Q_{avg}	m^3/s	0.73	0.50	0.27	0.49	0.08	1.27
q_{avg}	m^3/s	0.81	0.50	0.30	0.52	0.08	1.30
$W1_{avg}$	t/a	6221	2853	3286	3580	5587	9972
$W2_{avg}$	t/a	5576	2768	2966	3395	5587	9738
$[TDS]_{flow\ weighted\ avg}$	mg/ℓ	243	175	353	219	2109	243
n_Q		218	73	50	14	1	80
n_{TDS}		174	39	43	13	1	78

Table 20: Flow histories from industrial activities in the Leeuspruit catchment

Time stratum		**End Date**	**$[TDS]_{flow\ weighted\ avg}$**	**$W1_{avg}$**	**Q_{avg}**	**$W1_{avg}$ minus background**
Description	**Period**	**Median Year**	mg/ℓ	t/a	m^3/s	t/a
Pre industrial baseline	**1974-1982**	1978	166	2613	0.50	0
Introduction of mining	**1983-1991**	1987	353	3286	0.27	673
Reduction in mining load	**1991-1997**	1994	219	3580	0.49	967
Discharge incident (see note 1)	**1998**	1998	2109	***27933***	***0.38***	***13600***
stream flow	**1999-2008**	2003	240	9846	1.27	7233

Note 1: The DWA flow data set for 1998 in Leeuspruit has one very low value for flow (see Table 19) and a high component of industrial discharge (see Figure 9). Also a concentration does not indicate whether the mass flow is low or high. An additional method was needed to determine the 1998 flow for 1998. As the Waterval flows are complete for 1998 (see Table 21), and as average rainfall in the two catchments can be expected to be similar, the ratio of river flows was calculated for the base line period and the industrial periods. There is consistency in the first two industrial periods with the base line flow (average ratio of 0.089+/- 0.012). In other words the possible contribution by industrial flows is not statistically significant. For the final period, this ratio is four times higher and is not consistent with the previous 23 years. The salt flow measurement for 1998, can therefore be taken as an under rather than over estimate for this set of assumptions.

6.2 Salt flow measurements at C1H008: Waterval River below Sasol Mining Collieries, Harmony Gold, and Sasol SF complex, and Govan Mbeki urban complex

The C1H8 monitoring station was established in 1976 prior to the commencement of the large scale development at Sasol Mining and Sasol Synfuels Complex in 1979 to 1982. Gold mining commenced by 1958 (Mining Weekly, 1999) and for this reason there is not a pre-industry complex base line. The base line value for Leeuspruit has been used as the base line. There is an increasing trend in TDS in excess of the base line (Figure 11). The increased fractions of Cl and SO_4 are observed in the

Waterval River. An onset over a base line is not observed and this is attributed to the onset of gold mining in 1958 which precedes water quality monitoring in 1974, by 16 years.

As there has also been significant urbanization with water and sanitation services, a contribution to the flow and salt loading can be expected. The average of the TDS releases from the domestic sewage works is typically in the vicinity of 450-700 mg/ℓ for the sewage plants in Govan Mbeki (DWA, 2009). The increase in TDS is therefore expected to be associated with both urban and industrial activities of the complex. The contribution to the TDS by mining could be expected to be falling if the anecdotal evidence from interviews with stakeholders is considered. The main reason given is a tightening of regulations on mine water control by DWA.

The contribution to the base line TDS flow can be expected to be around 20 kt/a for the 2008 year when most of the production and salt flow data has been made available to the project. This compares with inventories releases: Sasol Synfuels of 3.3 kt/a, Evander Gold less than 0.032 kt/a; Sasol Collieries no leakage reported. Estimates of the Govan Mbeki municipality sewage works were taken in 2007. These indicated that (Wilsenach & Roux, 2008), of the three sewage large treatment works feeding the Waterval, only the Sasol plant was operating at full capacity at about 11 Mℓ/d. Govan Mbeki reported in 2009 that refurbishment was underway in 2009. For the period of the survey the through put of the system was estimated from the number of pumps in operation and was set to two times that of Sasol Synfuels sewage plant, i.e. at 22 Mℓ/d. An average TDS for the period was taken from the DWA records as 430 mg/ℓ. The comparison of the surface water flows and the industrial point source discharges is provided in Table 23.

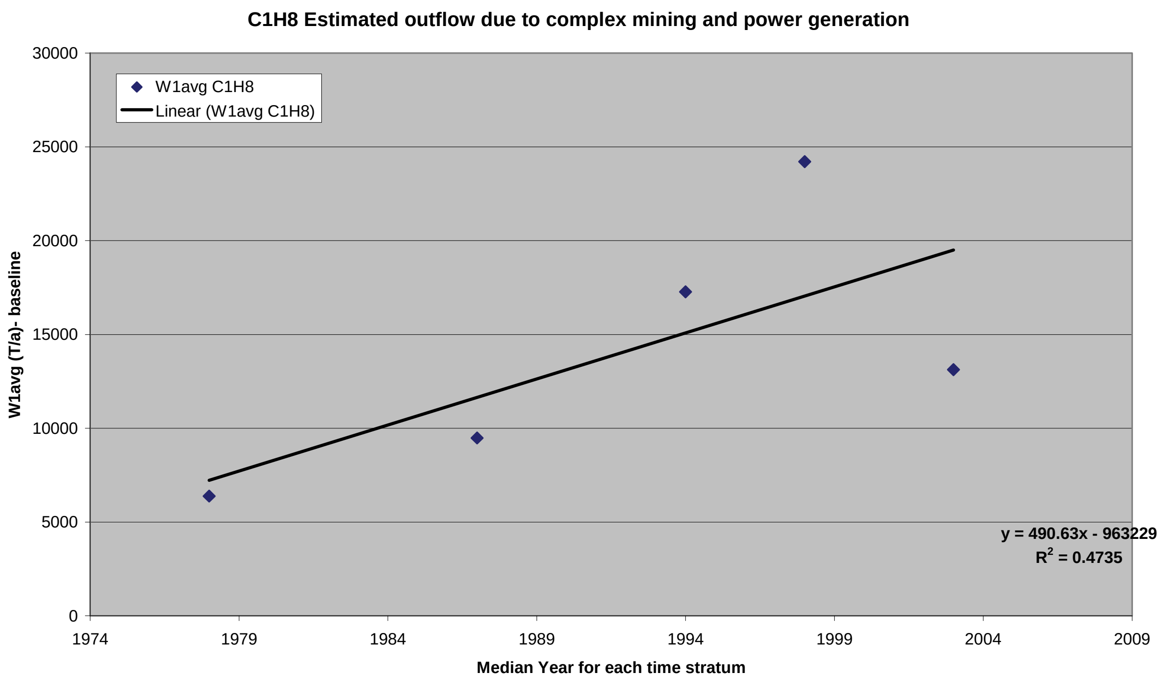


Figure 11: Estimated stream loadings due to mining and energy conversion in the Waterval River

Table 21: Statistics for flow measurement at C1H8 between 1974 and 2008

Parameter	Time Stratum					
	Units	1974-2008	1974-1982	1983-1991	1991-1997	1998	1999-2008
Q_{avg}	m^3/s	4.09	5.13	2.80	6.39	4.30	3.39
q_{avg}	m^3/s	4.27	7.22	2.91	6.39	4.30	3.50
$W1_{avg}$	T/a	35875	46796	25080	50705	46738	31864
$W2_{avg}$	T/a	34383	33244	24139	50705	46738	30840
$[TDS]_{flow\ weighted\ avg}$	mg/ℓ	267	205	273	252	344	289
n_Q		325	34	94	71	12	114
n_{TDS}		285	15	88	71	12	99

Table 22: Estimated flow from industrial activities in the Waterval catchment

Time stratum			$[TDS]_{flow\ weighted\ avg}$	$W2_{avg}$	Q_{avg}	$W2_{est}$ -background
Description	Period Yrs.	Median Yr.	mg/l	t/a	m^3/s	1st period
Increasing pH	1974-1982	1978	205	34383	5.13	6387
Commencement of mining and chemical processing; falling pH	1983-1991	1987	273	33244	2.80	9484
Increasing pH	1991-1997	1994	252	24139	6.39	17271
Steady pH and TDS	1998	1998	344	46738	4.30	24219
Falling TDS and pH	1999-2008	2003	289	30840	3.39	13127

6.3 Comparison of releases and stream loads to evaluate possibility of leakage

Sasol Synfuels is the only stakeholder with a permit for release of industrial waste. Discharge into the Waterval River is 9 t/d. The estimated flow for the municipal sewage plants is given in column 'WWTW'. The sum of these two flows is around half of the total load and indicates an unaccounted load of around 18 t/d. Industrial and mining point source discharges into the Leeuspruit have not been identified by DWA, Anglo-coal or Eskom. The 20 t/d estimate for 2008/9 cannot be allocated to a point source.

Comparison of industrial salt flows and capacity for storage of salts

Although the calculations of the storage capacity of the salts indicate that the capacity for storage is higher in some ions than in others, the net indication is that the amount of salts that can be disposed is less than the amount of salt that is being produced. This is consistent with the mass flow observations and the interviews that additional disposal capacity is being sought underground. It is concluded therefore that a key issue for the complex is the shortage of storage capacity.

An area of research is the long term disposal of salts in ash. An exceedence of ash-brine capacity is not clear as can be seen in the mass balances of water and salts where the amount stored in ash-brine co-disposal is not measured and is calculated by difference. However it is clear from the interviews that there is concern with the quantity of saline waste water and it is concluded that irrespective of the accuracies of the data provided for the study, there is a practical limit currently being experienced with the storage of salts when the industrial site is combined with a mining site. The contributing factor is undoubtedly the addition of salts from mine water to the long term storage requirements for the industrial processing sites at Sasol Synfuels and Eskom Tutuka. Replacement of potable water by mine water contributes approximately 300 t/d. In the case of the gold mine complex where process cooling water is not required, the evaporation capacity of the slimes dams and the very large evaporation rate at Leeupan appears to be in balance. Hence saline water storage is not an immediate crisis there.

The issue of water soluble salts in ash has been discussed with the industries. Definitive data on the soluble fraction is dependent upon the salinity of the water in contact with the ash, and the inflow of low salinity water such as rain. Potential contribution from Sasol ash is about 2 011 t/d (see Table 7) and from Eskom ash is 636 t/d (Table 14). This compares with the aqueous industrial waste load of 537 t/d from mine water (155 t/d) and treatment chemicals (382 t/d) (See Table 1). The mobilization of salts from ash storage is therefore a key factor in the management of the salts. .

Replacement of raw water by mine water saves around 20 Mℓ/d and 5 t/d of dissolved salts but costs an additional 224 t/d in waste salts from Tutuka mine water (62 t/d), Tutuka additional treatment chemicals at about ¼ of the mine water (15 t/d) (see Table 15), and from Sasol Mining mine water (49 t/d) and additional treatment chemicals at about 2 times the mine water (98 t/d) (see Table 8) . Bicarbonate is about half of a natural water system TDS, which does not cause a salination problem in the surface water system. So the trade-off in saving raw water by around 7% is a much larger increase in mine water salts.

Underground storage of mine water and brines appears to have a very practical limitation based on the flow of ground waters. Coal mining practice included long wall mining. Extensive fissuring of the strata conducts runoff water into the compartments. To maintain dry working areas, the mines must be pumped. This daily pumping is the cause of much of the salt being treated in the desalination plants at ESKOM and Sasol Synfuels.

The policy of replacement of Rand Water Board water with mine water was commenced after the design and construction of these plants in the late 1970s to early 1980s. Those designs were for storage of brine from water desalination for boilers, and for sludge from evaporation systems. Those initial designs were not compatible with mine water replacement of large quantities of raw water. The data indicates that salt storage capacity problems are exacerbated by this policy.

7 RESULTS AND DISCUSSION

The application of the findings on the mass flows can now be interpreted in the context of the objectives for the study.

7.1 Aim 1. Life cycle of the salts in the complex with locations of sources and destinations

Two life cycles of water salt flows have been identified in the complex (see Figure 5 in Section 4.2). In each life cycle the main cause of salination of water is the reaction between oxygen and sulphide. Acids from this reaction are neutralized by bases from the ground water flow and from mine rock. This neutralization and salination continues until the access to base salts is halted or the base minerals are exhausted. Acidification then proceeds to an equilibrium where the pH is determined by concentrations of metal cations.

Examination of the water compositions indicates that the source of the salts is underground areas where water is pumped from the mine in order to allow extraction of ore and coal.

A second and potentially larger cause of salination is the dissolution of mineral salts in coal ash. An upper limit to the amount of aqueous salts that can be released from these ashes has been estimated for ash inventories in Sections 5.2 and 5.4. An operating limit in the ash-brine storage systems is not available. All these salts are contained in disposal sites and the leakage is dependent upon the porosity of the linings and the rate at which unsaturated salt solutions can flow through the disposal site. These flow rates are not known.

A third and site specific source of salt occurs at Sasol Synfuels. This formation is evidenced by the higher fractions of F, Cl, and SO_4 ions in the quench unit liquor, as compared to these ions in the streams of mine water and cooling water (see Table 8 of the Sasol Synfuels water and salt balance). These salt formation processes are assigned to increased volatilization of halide compounds at gasification temperatures in the Unit., and the oxidation of sulphide gases with quench water to form SO_4.

A fourth salt source is water treatment chemicals used for desalination. This source is approximately half of the mine water salt flows (see Table 1).

The possibility for salt formation from un-oxidized sulphides in the slimes dam is not supported by the mass flow analysis (see discussion in Section 5.6 and flow values in Figure 8). The upper limit for the data set provided by Evander Gold is likely to be around 1 t/d or about 5% of the salt flow for that site. The main causes for uncertainty are unmeasured leaks and the use of an estimate for the evaporation rate.

7.2 Aim 2. Quantification of the salt flows

The summary of the main aqueous salt flows in industry can be now provided (see Table 1) from extracts of the main flows identified for each of the five industries in the complex. These are provided for each industry as follows: Table 2 for Sasol Mining; Table 4 for Sasol Synfuels; Table 13 for AngloCoal New Denmark Colliery; and Table 18 for Evander Gold.

The long term trends in surface water flow and salination is provided in Section 6. The imbalance between industry and nature indicates that additional flows have yet to be identified. As a major concern is uncontrollable non-point source releases from mines this indicates that a key factor for long term management of environmental sustainability is the ability to differentiate between leakage and unidentified industrial releases.

An indication of the environmental impact is provided by the long term increasing trend to increasing salinity of the river system. For the measurement period of 1999 to 2008 the average unallocated load is about 6% (38 t/d) of the total aqueous salts generated by the case study area. Other indications are the increase in raw water use efficiency by use of mine water, the amount of mine water generated per unit of electrical output from Eskom Tutuka and long term trends for salination and pH in the rivers.

Specific water usage for the 2008/9 year is 1.9 ℓ/kWh. The raw water use is 1.72 ℓ/kWh and the mine water use is 0.18 ℓ/kWh. The amount of mine water produced per kWh is calculated from the amount of mine water discharged per day from New Denmark mine, and the amount of electricity sent out from the power station for the coal supplied each day to the power station (see Table 23). This provides a value of 0.3ℓ/kWh.

Table 23: Mine water production from New Denmark Colliery per kWh power from Eskom Tutuka

Mine Water (Mℓ/d)	17
Coal New Denmark (kt/d)	12.3
Coal Total (kt/d)	30
Power (GWh/d)	54
ℓ/kWh New Denmark	0.3

Long term trends for pH have been observed in the data, but are not reported here. These correlate with the life cycle of salt formation described in Figure 5 in Section 4.2, i.e. start at the background, increase with mining and then fall.

This quantification enables estimates of the potential for reduction of salt flows by integrated Eco-efficiency projects.

The two largest sources of waste are Mine water and Water Treatment Chemicals (see Table 1). As discharge of Mine water accounts for about half of the 600 t/d of salt produced by industrial operations, high priorities are to reduce salination underground, and to reduce the quantities of Mine water produced. WRC recommends techniques to reduce salination underground (Pulles et al., 2008; Pulles et al., 2008). The most important is to segregate fresh and useful ground water from mine water and reactive minerals in the mine. Other recommendations are to pump the groundwater so that mine water amounts are reduced.

The second priority is to change from desalination technologies that produce more salt than they remove. Salts from water treatment chemicals contribute around 155 t/d, i.e. a quarter of the industrial aqueous salt load. The desalination technique which produces the largest source of salt is Ion Exchange. Reverse Osmosis is the most effective high volume desalination process. The Evaporator Crystalliser is the most efficient desalination technique but is not used for high volume desalination or commercial salt production.

7.3 Aim 3. Can waste from one industry be used as raw material for a second industry in the complex?

The main waste stream of concern is the underground flows of mine water. Three applications where mine water is used to assist production, and therefore, have an economic benefit, have been identified.

- Mine water from Sasol Mining, and AngloCoal New Denmark, is desalinated and used for cooling water, boiler feed water in processing industries (Sasol Synfuels, and Eskom-Tutuka).
- Mine water from Sasol Mining and New Denmark, is used untreated, for coal processing wash water, waste coal, slurry transport water and for dust suppression on coal mine processing areas and stock piles. The residual salts which are transported off the site as Coal Water on exported coal are not considered an environmental problem for their purchasers.
- Mine water from Evander Gold, is used for the transfer of slimes waste from the Metallurgical to the Slurry Dams.

Raw Water savings are made by desalinating mine water. This meets the main condition of integrated Eco-efficiency projects in the case study area.

7.4 Is environmental performance being improved as the result of the mine water desalination Integrated Eco-efficiency project?

The second condition for an Integrated Eco-efficiency project is incremental improvements in environmental efficiency through the transactions.

It is now established that the current approach to management of mine water is environmentally inefficient, because the desalination produces more waste salts than are removed. Areas not clearly demonstrated in the mass flow analysis are:

- The capacity of the ash-brine, and mine water disposal technologies to accommodate the additional salt loads
- The environmental sustainability of the uncontrolled discharges to the surface water drainage system.
-

7.5 Key factors affecting the environmental sustainability of the salt storage systems

The long term trend on increasing salinity in the surface water systems due to mine water salts indicates that the issue of salt storage is a key factor in the long term environmental sustainability of the region. In-house non-public research is on-going for efficiency and safety of salt storage. Six candidate salt disposal and storage systems have been proposed for long term environmental stability. These are:

- Ash-brine co-disposal sites with brine spraying for dust suppression
- Ash-brine co-disposal sites with desalination of ash-water to produce cooling water and process water
- Evaporation dams
- Slimes dams
- Underground disposal of mine water in coal mines,
- Underground co-disposal of brine with mine water recharge in a sealed coal mine compartment.

Other disposal mechanisms available to the mines include

- Dust suppression of coal stockpiles using mine water
- Fine coal discard and coal rock co-disposal sites which using slurry transport of sub 100 µm fines, and evaporation of the slurry water
- Dust suppression of working areas, e.g. coal processing areas, with run off collected in run off dams.

In-house and non-public research and development data obtained to date are described as preliminary and subject to further research, and therefore not publishable. The monitoring of long term trends such as diffusion of salt release cannot be linked to the long term trends of increasing salination of the surface water systems. Without the information integrated eco-efficiency projects cannot be established.

> ***The first key factor is therefore the monitoring of the integrated environmental performance of the case study region, and the identification of projects that will halt the increasing trend of salination of the surface water system. These will include projects to locate and monitor the non-point sources of salt release in the system.***

Leakage data is available for aqueous salts from slimes dams (Section 5.6). Storage capacity in a slimes dam is higher for Ca, Mg and SO_4, than Na, K, Cl, and F. This is consistent with the solubility data. Storage capacities for these salts are also higher in ash-brine co-disposal sites as reported

Section 5.2. However, the correlation with this storage capacity and TDS flows in the Waterval and Leeuspruit have not been made.

The economics of eco-efficiency projects requires that economic efficiency is demonstrated. Storage systems capacity and costs should therefore be quantified in order to enable integrated project sharing of costs and risks.

> ***The second key factor is the provision of engineering performance data for each candidate disposal technology. This will quantify the amount of salt from mine water that can be stored in each of the candidate aqueous salt storage systems.***

7.6 Key factors affecting the adoption of integrated eco-efficiency projects in the case study area.

The experience of the mine water desalination project can be used to understand how integrated eco-efficiency projects in the area can develop and can be improved.

Integrated project agreements have been made with DWA and Eskom Tutuka and AngloCoal New Denmark, and Sasol Synfuels and Sasol Mining. These have been driven by DWA who has imposed restrictions on the amount of raw water in exchange for permission to transfer mine water waste to the processing plants. The intention appears to have been to use mine water for evaporation of waste heat. Not the intention to overload the salt storage system

What appears to be missing from the these project agreements are

- high level regional overview of the technical and economic alternatives to increased storage and disposal capacity, and
- Understanding of the long term environmental sustainability of the current approach, e.g. importing 20 Mℓ/d of mine water with 110 t/d of salts to replace 20 Mℓ/d raw water with 5 t/d of salts.

As now shown in this study, high level understanding of impacts and potential for integrated technologies is assisted by an integrated assessment of the sources and destinations of salts, i.e. a life cycle assessment of flows of salts and water.

During the case study the alternatives were considered, the most notable being the recovery of saleable salts from the waste salts. Evaporative crystallisation provides clean water and saleable salts, and produces less waste than it treats. Advice was that the technology is not technically and economically viable. Alternative projects in the underground mines, e.g. segregation of fissure water is considered infeasible. The extraction of fissure water or ground water to avoid high level salination was not raised as an option by the mines.

It appears that an economic and environmental cost benefit study did not integrate salt storage with water supply options. Options for 20 Mℓ/d of mine water have not been considered, and the options for reduced mine discharge have not been raised. It is concluded that a long term economic and environmental sustainable model is not being considered in the public domain. As salination of fresh water resources is a national issue, the learning from this case study will extend beyond the needs of the individual industries and the regional interests of DWA.

A framework for development of an integrated Eco-efficiency project has been proposed for South Africa (Brent et al., 2008) and is summarized in Figure 12. In the context of this proposal, the study has identified the following conditions for the levels in Figure 12.

- Level 1. Constitution. Agreement in principle on the need for continuous environmental improvement has been made by each of the industries, and DWA who is the main authority.

- Level 2. Identification of unsustainable technologies. This study has not highlighted the technologies that produce more salt than they remove. This practice is not sustainable in a closed system.
- Level 3. The development of economic incentives and regulations that are consistent with the economic and environmental sustainability problem appears to be missing from the current integrated projects. It can be expected that unless these conditions are met, then contradictions in the management of the operating system will occur. For example, if the permitted salt storage systems are not environmentally sustainable, then the responsibility for post closure liabilities will be managed sub-optimally.
- Level 4. The two measurements of environmental sustainability that has been provided are in the processing industries, i.e. Sasol Synfi.e.ls and Eskom Tutuka. These are the measured savings in Raw Water consumption by desalination of mine water, and the elimination of salts from the surface water system by storage on site. However these are not the only measurements of resource efficiency and environmental efficiency. For example the specific water usage of Eskom does not account for the amount of mine water that is produced. The amount of salt used to remove the salt is also not measured. For this reason additional measurements of environmental performance are needed by the industries and DWA.

International experience in Australia (Bossilkov et al., 2005) and Norway (Rogers & Banoo, 2005) indicates that successful Eco-Efficiency projects require regulations for reduced resource consumption, and economic support systems. Energy efficiency was the basis for the integrated Eco-efficiency project in Australia. Regional economic incentives supported projects that reduced electricity consumption. These were used to establish viable integrated projects. Recycling of domestic, mining and industrial waste heat, e.g. from roasting of sulphide ore, were used in Norway to reduce oil and gas consumption. The Norwegian projects were supported by national waste recycling incentives, e.g. deposit systems with waste to energy regulations, and agreement to invest in new technologies at the time of the permit negotiation.

In the case study area each industry has committed to the principles of continuous improvement of resource use efficiency (Anglo American, 2010b);(Sasol, 2010)(Harmony Gold, 2010). However what is not clear to the study is how the economic incentives and improved environmental sustainability can be linked to reductions in operating costs and post closure liabilities for waste salt and saline water storage.

Box 1

Level 1. Principles for the constitution of the system

- IE argues for systems interdependency between economic and social subsystems and the parent ecosystem
- IE contributes to material and energy flow principles
- IE systems and networks philosophy has the potential to contribute to social principles, e.g. with inter-organizational corporate social responsibility management

Level 2. Principles for a favourable outcome of planning within the system; principles for sustainability as the desired outcome

- IE provides material and energy flow limits and thresholds of ecological sustainability

Level 3. Principles for the process to reach the above outcome of sustainability, e.g. principles of sustainable development to research sustainability

- IE offers planning principles

  AND/OR
- IE offers constructs that can be used as hypotheses in sustainability systems analysis, from which systems planning principles can be derived

Level 4. Actions and concrete measures

- IE offers suggestions for material and energy flow reduction
- IE offers suggestions for material and energy flow substitution, e.g. recycling of matter and cascading of energy
- IE provides a network and systems approach for these reductions and substitutions

Level 5. Tools and metrics to monitor and audit

- IE offers inter-organizational management systems and concepts, e.g. regional environmental management and auditing systems (REMS)
- IE can be used to develop systems-level indicators
- IE suggests for 'what if?' scenarios, the economic, ecological and social effects of which one can measure and calculate for decision-making, policy and management

Figure 12: Hierarchy of conditions proposed for an Integrated Eco-efficiency project (Brent et al., 2008)

These observations lead to two additional key factors.

> ***The third key factor is the need for data which demonstrates to the DWA and to industry those eco-efficiency technologies where profitable business can be made from salt waste management. Such data will assist industry to make technical decisions on how to proceed with and to prioritize options for improved environmental performance.***

> ***The fourth key factor is the application of controls on access to resources, with the objective to increase the value actions to improve cleaner production, e.g. avoidance and recycling. These controls will enable industry to decide on how to improve economic performance using the available options to improve environmental performance.***

8 SUMMARY

The objective of integrated eco-efficiency research is to develop projects that have incremental economic and environmental benefits.

The objective of this inventory preparation with industry and DWA was to get an understanding of the potential for integrated projects from an understanding of the quantities, sources and destinations of salts and the technologies that increase or decrease this load. The environmental sustainability is improved if the load on the ecosystem is reduced. The economic sustainability is improved if the security of supply is improved. Security of supply is managed by two instruments, control access to resources to ensure protection of the resource, and pricing of resource to ensure that demand matches supply. Resource efficient technologies will improve productive use of the resource. There are two loads on the natural systems, one is water demand which affects sustainability of quantity of supply; the other is disposal of salts which affects quality of supply.

A number of findings have been made in the process of collecting and interpreting data.

Two integrated eco-efficiency projects are in operation. Both take waste mine water from one industry, and recycle it to produce boiler feed water and cooling water. The desalination technologies are reverse osmosis, ion exchange, hot lime softening, evaporator crystalliser, vapour evaporation, and electro-dialysis reversal. The environment benefit explained is an incremental improvement in the productive use of raw water. Specific water usage is reduced from 1.9 ℓ/kWh to 1.78 ℓ/kWh for raw water. The economic benefit is the ability to operate the plant and equipment technologies built at the time of the commissioning of the plant for boiler feed water supply and cooling water supply. The additional economic costs of desalination, and storage and disposal of saline and brine water have not been obtained. Also the economic costs of post closure liabilities have not been addressed.

Due to the absence of performance data on salt storage and disposal capacities and leak rates, and the active evaluation for alternative salt disposal capacity, it appears that the existing salt storage and disposal systems are overloaded. The unaccounted for loading of industrial waste in the surface water flows is linked to the industrial salt inventory, but there is not enough data is not yet complete.

What appears to be missing is a high level life cycle assessment of the technology alternatives to the current salt problems. For example can the salt disposal problem be replaced with a reduction in mine water salinity problem? Or can ground water pumping avoid mine water discharges during the operating phase of the underground mining? In waste management terms the approach being followed by industry and DWA is an end-of-pipe strategy. The alternatives that are first evaluated in eco-efficiency are avoidance or minimization strategies, as these in the long run are usually more sustainable. They do require however new process technologies. The integrated eco-efficiency option will have four requirements for success;

- Construction of a resource conservation regulatory environment that incentivises resource conservation projects;
- Construction of an economic supply and demand model to ensure that demand does not exceed supply;
- Incremental improvements in resource efficiency; and
- Incremental improvements in economic efficiency.

The current approach appears to contain one of these requirements, i.e. the regulatory resource conservation environment requires that 10% to 5% of the raw water supply is replaced by mine water.

Economic incentives to recycle waste mine water and incremental economic benefits have not been clearly articulated by industry and DWA during the research for this report. The environmental loads of salts have increased rather than decreased with the technologies in use. Other viable alternatives to desalination have not been proposed by industry or DWA.

Therefore the environmental and economic sustainability of the current operations are not clear. Within the paradigm of integrated eco-efficiency projects, new projects are required if the current storage and disposal systems are to improve environmental sustainability.

9 RECOMMENDATIONS FOR FUTURE RESEARCH

The use of life cycle thinking is required to provide a holistic rather than an industry boundary view. The technology options should be based on cleaner production principles and eco-efficiency project agreements, i.e. where economic benefits and environmental benefits are obtained by industry and the authorities who control the resources

- The first recommendation is to include life cycle thinking to the interpretation of environment impact and opportunities for integrated eco-efficiency projects. A task is to identify and assess options that will reduce the salt load rather than increase the load when mine water is used. Incremental savings are targeted in mine water, coal water, desalination, and conversion of salts to other minerals can now be proposed with potential benefits.
- The second recommendation is to define the sustainability problem for the whole of the case study area. First get a balance on the salt flows and then identify the technologies for salt management that explain the current shapes of the salt loading trend lines in Figure 10 and Figure 11. The most important technology will be targeted for improvement projects.
- The third recommendation is to review and recommend incentives and regulations that are consistent with successful outcomes of the targeted technologies identified in the study, or in integrated eco-efficiency projects in use internationally and in South Africa. The approach followed in the energy sector may be of use for the water sector.
- The fourth recommendation is to consolidate all the research and operational data, public and non-public, and develop a set of guidelines for salt storage and disposal from the capacities and costs for the conventional ash and brine from mine water salts. This data can be used to establish incentives and regulations for industry and the authorities. It is now clear that there is an urgent need to provide direction for the salt and saline water management in inland mining and processing industrial complexes.

10 ADDENDUM: COMMENTS, QUESTIONS AND ANSWERS TO THE REPORT AFTER COMPLETION OF THE INVENTORY

WRC requested comments from DWA and the industries in this inventory report. Sasol mining and Sasol Synfuels prepared a list of queries in the text of the circulated draft. The response to those comments is summarized below.

- Sasol Synfuels confirms that the operating limit of the mineral salt dissolution and trapping in the ash salt storage systems to be upper limit of 7% which was used in the assessment of the salt storage capacity of the ash brine storage systems. The public domain data to support this is contained in the following reports (Gitari et al., 2008a; Gitari et al., 2008b; Vadapalli et al., 2008)(Vadapalli et al., 2008; Gitari et al., 2009; Hareeparsad et al., 2010; Fatoba et al., 2008; FATOBA et al., 2010; Mahlaba et al., 2011c; Mahlaba et al., 2011a; Mahlaba et al., 2011b).
- It is agreed that it is unlikely that the entire salt component in coal water on gasifier coal is trapped in bottoms coal ash during the high temperature and pressure processes occurring during the gasification process. It is a valid assumption to assume that salts from gasifier ash are trapped in gasifier scrubbing liquor.
- Sasol mining queried: The term fissure water which it considers is used to describe water flows to working areas only for in gold mines. Ground water is used to describe water flows into coal mines.
  Authors: The use of fissure water to describe flows into coal mines is based on the convention used in the previous WRC study on mine water management by Hodgson (Hodgson & Krantz, 1998). It is explained in the diagram of water flows in the life cycle as shown in Figure 1. Ground water flows are demonstrated to be lower than the fissure water flows by the rapid recharging of coal mines immediately after rain fall, and the slow discharge from ground water dry spells.
- Sasol Synfuels agrees that mine water salts may be transferred to the ash system. But the amount is expected to be lower than allocated here.
- Sasol Synfuels advises that the amount of sulphates in the mass balance are reduced by the amount of sulphur that is removed from the syngas stream and sold as elemental sulphur CSIR notes that the gaseous H_2S stream is not trapped in the hot gas liquor and therefore does not affect the contribution to salts included in this inventory.
- These additional inputs to the study do not change the overall findings and recommendations for additional research.

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