ESTIMATING THE IMPACT OF SITE HYDROGEOLOGY ON GROUNDWATER LIABILITY, CLOSURE AND REHABILITATION

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ABSTRACT

The generation of waste material associated with Gold Mining activities is a reality. Research on this waste material has recently expanded worldwide in an attempt to scientifically characterise and understand the interaction of this waste material with the natural environment. The increase in awareness of environmental issues and the demand for a cleaner environment by the public has resulted in gold mining companies placing greater emphasis on the continuous rehabilitation of harmful impacts caused by mining operations. Ongoing rehabilitation is also a requirement of the Government Departments involved in mining in South Africa. The most pressing concern for the relevant Government Departments is the potential of uncontrolled pollution of water resources in the vicinity of the mines, especially after mine closure.

The key focus of this paper is to discuss methods to scientifically assess the “source-pathway-receiver” environments based on the site hydrogeology. Most importantly, the approach taken needs to be practical and affordable to the mines as well as acceptable to the authorities. Ultimately the process followed in this paper has led to the development of a logical approach to the estimation of groundwater liabilities in a typical gold mine environment. The term groundwater liability is defined as all environmental, financial and legal compliance risks associated with a specific source, pathway and receiver.

1. INTRODUCTION

Historically, South Africa has been the largest gold producer in the world (Atomic Energy Corporation of South Africa, 1990). In 1996 alone, a total volume of 377 million tons of mine waste were produced, accounting for 81% of the total waste stream in South Africa (Chamber of Mines of South Africa, 2001). As the mining and industrial activities in South Africa increased from the turn of the century, so did the contamination of the Vaal River and other important surface water bodies increase.

Mining is by definition a non-renewable activity and the inevitable fact of starting a mine is that mining will cease at some point in the future (Hodgson, 2001). As mining and environmental legislation developed since 1994, t it has become more and more difficult for the mining industry in South Africa to obtain a permit for closure. This is often because insufficient information is available to confidently predict the long-term impact that the mine may have on groundwater resources in and around the mines. Another complicating factor is that the information available is not always presented to authorities in a form that is understandable, practicable and reflective of pro-active management.

It is important to understand the impacts of mining on the groundwater environment during the operational phase of mining but also to develop a logical approach to assess these impacts towards mine closure. Many elements toxic to humans, animals and vegetation occur in surface effluent water and leachates from mine waste storage facilities. It is important that the impacts identified be quantified in terms of the distance it will spread from the pollution source and the timing of such impacts. It is however also important to put these impacts into perspective and to develop a site specific, practical, straightforward and understandable groundwater assessment tool for management and planning purposes..

AngloGold Ashanti South Africa Operations’ Environmental Management Department (AGA) and GCS (Pty) Ltd Environmental Consultants (GCS) have developed a cost effective strategy to identify, assess and understand risks and liabilities associated with long-term groundwater contamination associated with gold mining activities.

2. APPROACH

Monitoring and determining the impact that waste facilities (such as waste rock and tailings storage facilities) have on surface and groundwater resources quality, is a complex and multidisciplinary task.

The type of waste material, amount of waste, potential of leachate generation and vulnerability of site aquifers are all unknown aspects that need to be addressed before a management tool can be developed. To assess the liability of groundwater contamination for closure purposes, hydrogeological data is translated into hydrogeological conceptual site models (HCSM) which are subsequently used as the basis for predictive models to allow simulations of given field conditions. The outcome of these simulations is used as a guide during the decision making process. Technical data is then further processed as part of financial feasibilities models and legal considerations.

The reliability of these models and consequent understanding of site hydrologeology is, however, influenced by the quality and quantity of data available for consideration. Thus, in an ideal case, data should be available for all variations in site conditions, be they geological, chemical, hydrological or physical. In reality, though, it is either not possible or cost-effective to account for all possible variations, particularly where there has been a significant disruption to the natural environment from human activities on a large scale.

To understand groundwater liabilities and to be able to supply mine management with sound guidance, an approach of step-by-step assessments, based on the "Source-Pathway-Receiver" principle was developed by GCS and AGA. In this instance, a cost-benefit approach was taken to the investigation by complimenting existing data with previously undetermined site parameters. The term "source-pathway-receiver" was applied during the technical assessment phase and for the development of the HCSM. To understand liability and risk, hydrogeological, financial, legal and public health aspects were included in the evaluation. The following diagram illustrates the process applied by GCS for the AngloGold Ashanti South African Operations:

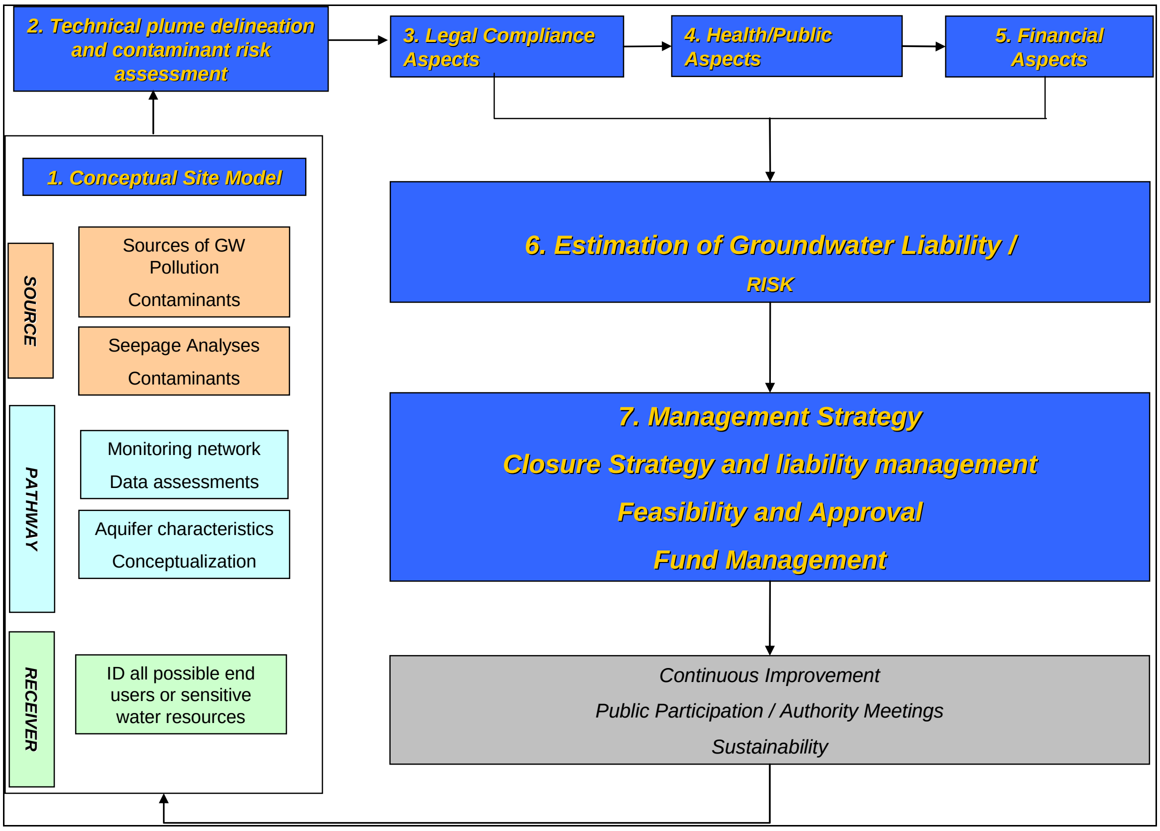

Figure 1. Flow diagram illustrating the groundwater management approach.

3. DEVELOPMENT OF A CONCEPTUAL SITE MODEL

The source-pathway-receiver model provides a conceptual portrayal of the mode through which contaminants act and the potential harm they may inflict on a receiving water body and/or organism. The conceptual model is used to develop management action plans and reclamation alternatives that are directed toward mitigating potentially harmful effects caused by the contaminants of concern.

Understand the Sources

The primary objective is to be familiarised with operational issues that can or already have impacted on local water resources (groundwater and surface water). Groundwater impact sources can be classified as follows:

1. Change in groundwater quantity:
    a. Mine de-watering,
    b. Groundwater supply well- fields, etc.
2. Change in groundwater Quality:
    a. Seepage from waste storage facilities like tailings and waste rock through ARD (acid rock drainage),
    b. Seepage from dirty water storage facilities,

c. Poor quality leakage from old and redundant open pit and/or underground mines through AMD (Acid Mine Drainage),
d. Poor quality seepage from other surface infrastructure like metallurgical plants, workshop areas (mainly hydrocarbon contaminants), etc.

The West Rand aquifer has been significantly polluted by the disposal of mining related waste on surface (Fleischer, 1981). Tailings storage facilities (TSF) from the gold mining industry are the main contributors of sulphate to the groundwater in this area. In the years before sufficient understanding of aquifer mechanics was available, it was thought to be sound practice to place TSF on top of dolomitic aquifers. This ensured stability of the facilities, as much of the retained water drained vertically through the TSF into the aquifer below. In areas around the Klerksdorp Gold-fields, the West Rand as well as the East Rand Gold-fields, many TSF are located directly on dolomitic aquifers.

Environmental legislation changed significantly in the past 10 years and mines are now required, through legislation, to conduct environmental impact assessments before a TSF location is approved by authorities and constructed by the mines. Construction of new TSF on sensitive aquifer systems is regarded as one of the main fatal flaws in project planning.

For the purpose of this paper, focus will be placed on contamination from older pre-2000 TSF.

The sources are mainly assessed by the following common practice:

- Laboratory analyses on waste material to determine leachate potential and main contaminants associated with the waste material. The process is usually started off by obtaining material samples for static leach testing and acid base accounting (ABA). Additional and more detailed kinetic testing can be applied to obtain a better idea of long-term leachate characteristics. Information from a number of reference studies is available to guide this process. ABA and kinetic tests will supply answers on the capacity of the material to buffer acidity as well as on subsequent metal and sulphate leaching. Figure 2 indicates a typical gold mining environment with some of the test work applied on tailings, waste rock and other sources of possible contamination (Google Image of a section of the Klerksdorp-Orkney-Stilfontein-Hartebeestfontein (KOSH) area in North West Province, South Africa).
- Water monitoring and other on-site surveys supply additional information on source behaviour. It is important to identify indicator elements for different waste sources.
- Water Balance calculations will supply an indication of seepages from the facility. Von Bredow (1995) suggests that tailings dams produce a variable and unpredictable quantity of effluent. As part of the AGA approach an attempt is made to assign values to these “unpredictable” quantities. Two types of TSF exist in the study areas:
  - Operational; and
  - Decommissioned.

  For assessment purposes, a simplified conceptual model was developed and applied; the model was developed by PHD in 2002 when AGA completed a geochemical assessments of the waste facilities. Four zones were identified as water pathways (Figure 3) during the study:
  - Zone 1 – the unsaturated zone.
  - Zone 2 – the saturated zone.
  - Zone 3 – the slope zone (this zone will be assumed unsaturated).
  - Zone 4 – the mixing zone for geochemical modelling.

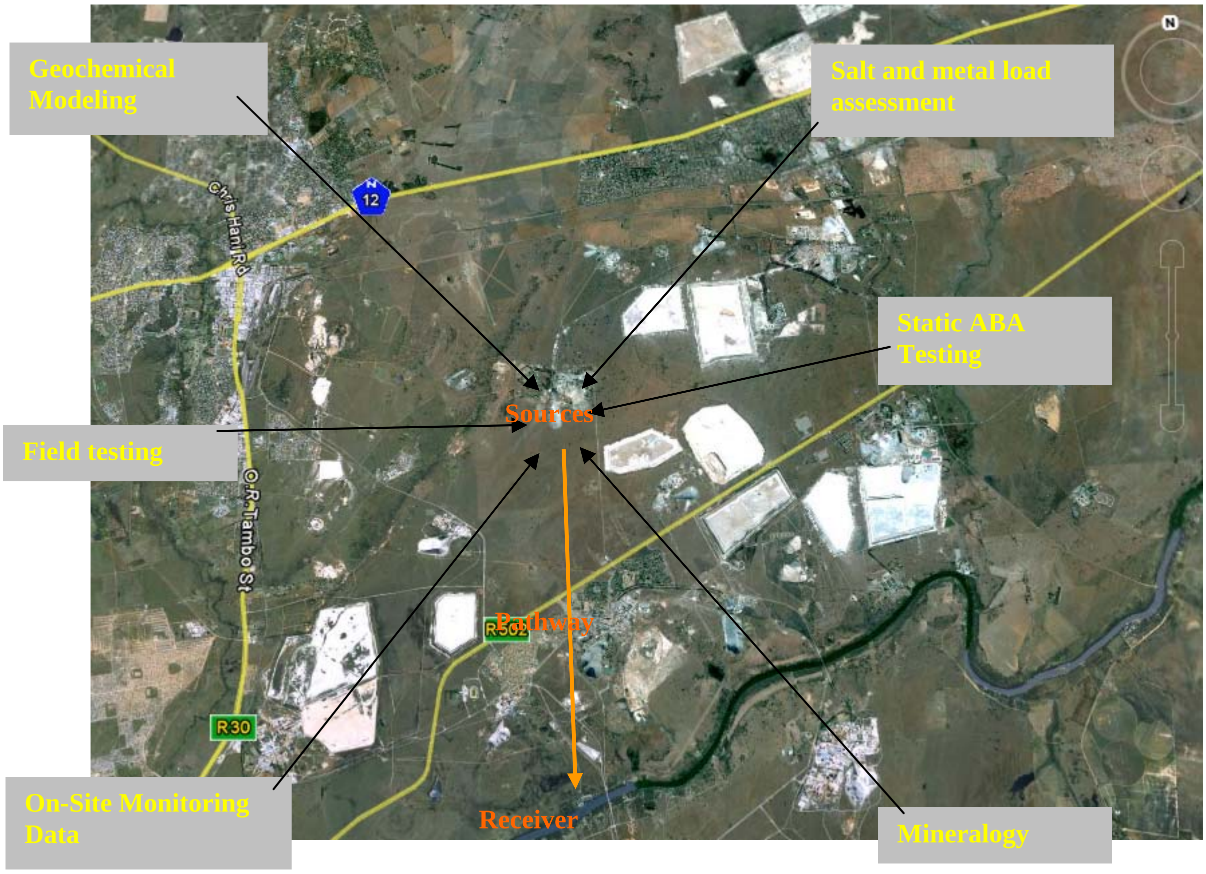

Figure 2. Assessment of sources and Google Image of the KOSH area

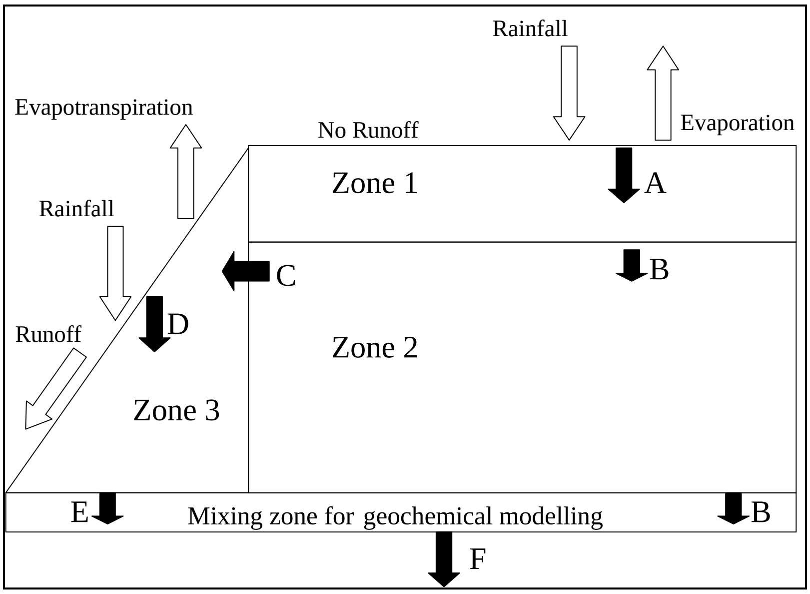

Figure 3. Conceptual model for tailings dams (PHD, 2002)

Several mechanisms provide for contaminant release from the tailings and other mine wastes like the waste rock dumps:

- Precipitation runs over the material and carries dissolved and suspended contaminants to surface water bodies.
- Precipitation percolates into the mine wastes and mobilizes contaminants into underlying soil and aquifers.

After the assessment phase has been completed, it is important to capture all data into a dedicated database.

Table 1 shows a summary table that can be developed for a given site for database purposes.

Table 1. Example of Source list for a mine

	Source	**Type**	**Flow type**	**Barrier Type /Geology**	**Approx Area (ha)**	**Tests**
West Area						
1	Old TSF Compartment 1	TSF	Saturated	SHL/SS/CHRT/DOL and Tailings	152.0	Samples, ABA, Static and Geochem model
2	New TSF Compartment 2	TSF	Saturated	SHL/SS/CHRT/DOL and Tailings	152.0	
3	Dirty water Dam 1	Dam	Saturated	Clay lining	2	
East Area						
1	WRD 1	TSF	Unsaturated	SHL/SS/CHRT/DOL and Tailings	152.0	Samples, ABA, Static and Geochem model
2	TSF 1	TSF	Saturated	SHL/SS/CHRT/DOL and Tailings	152.0	
3	Return Water 1	Dam	Saturated	UpVC Liner	2	

From the completed test work one will be able to identify what the main contaminants are and how these will behave and react. For the purpose of this paper, the characteristic leachable elements are sulphate ($S0_4$), iron (Fe) and pH (to determine the level of acidity). It must be noted that this provides a simplified version of the full geochemical analyses.

Understand the Pathway

The second step in conceptual model development is to understand the pathway which the contaminants will follow. Pathways are usually aquifer systems or surface water streams or a combination of sub-surface and surface movement. Pathways can sometimes be wind blown dust which settles on open water features and result in some degree of contamination. This part of the investigation entails the gathering of, as many as possible, geological and hydrogeological reports as well as background information. Physical field investigations should also be incorporated.

The following list typical steps to be followed to enable a better understanding of site aquifer or pathway systems.

- Asses the general geographical settings to obtain an understanding of the regional environment,
- Assessment of all available geological and hydrogeological information,
- Assessment of all available monitoring data (including surface water sample sites). The following table (Table 2) can be used as a guideline of groundwater data that should be collected,

Table 2. Typical borehole data to be captured

	BH ID	**X,Y**	**Z**	**Description**	**Date Drilled**	**Geology and water strikes (m)**	**BH Depth (m)**	**Avg Water Level (m)**	**BH Yield (l/s)**	**Aquifer Test**	**Main chemistry**
1											
2											

- Conduct a gap analyses to identify short-comings,
- Field assessments, drilling and testing to obtain information to overcome data gaps,
- Initial analytical calculation.

The end deliverable of the “pathway understanding” is usually a sequence of conceptual cross-section diagrams presented with tables on aquifer flow parameters and preliminary flow calculations. Figure 4 can be used as a simple example through a typical gold tailings dam and associated sub-strata.

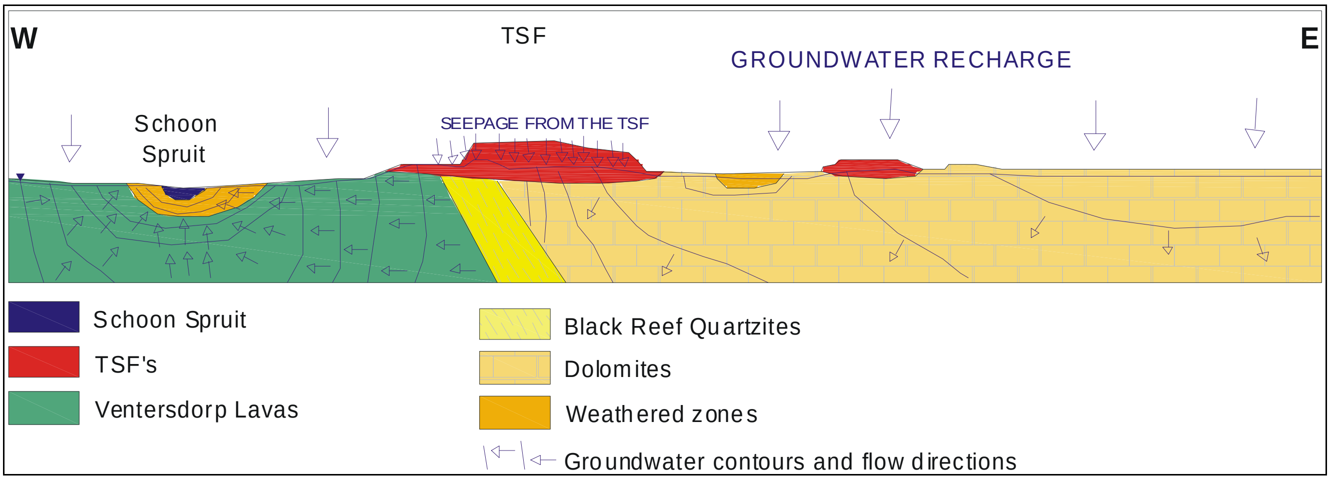

Figure 4. West east cross- section and geohydrological concepts (GCS, 2005)

Preliminary analytical calculations can be performed in order to determine the potential seepage from the identified contamination sources (as per initial impact rating exercise). These figures will supply very important initial information regarding seepage quality and quantities. For this spreadsheet type of analytical models, various other pre- and post-calculations are required. Some of the important calculations include:

Hydraulic Conductivity:

$$K = \left(\frac{Q}{A(dh/dL)} \right)$$

Groundwater gradient:

$$I = \frac{h1 - h2}{L}$$

Darcy flux (m/d) and flow m^3/d:

$$V_{Df} = KI \qquad\qquad Q = KIA$$

Where K = hydraulic conductivity, A = area of source, h = hydraulic head in the aquifer; L = cross sectional length; and Q = the cross sectional flow volume

Understand the Receptors

Receptors can be classified as the end-user of water resources; sensitive environmental entities like an aquifer system with a high yielding capacity; or one of the main rivers in South Africa.

4. TECHNICAL PLUME DELINEATION AND CONTAMINANT MODELING

After comprehensive conceptualisation of the mining, aquifer and regional surface water systems, the direction and extent of contaminant transport in groundwater needs to be determined.

This entails the collation of data so that it can be imported into a numerical groundwater modelling code. The MODFLOW code was applied for the predictive assessments in this paper. The simulations will ultimately provide answers on groundwater flow direction, characteristics regarding the interconnection between the waste sources, the groundwater and the receiving water bodies and behaviour of contaminants in the aquifer. The real value of hydrogeological modelling should be unlocked by using results for further conceptualisation, predictive and decision-making purposes. It is therefore important to understand the transport path from the waste source to the end environmental receiver. It is important to note that data received from geochemical modelling, unsaturated seepage modelling and other applications could be required as input parameters for the groundwater flow and contaminant transport model. Examples of geochemical applications can be Phreeqe, Geochemist Workbench, etc.

The receiving point of contaminants migrating through the aquifer along the identified paths must be identified and translated into a site-specific impact and risk assessments. In this way, the direct impact on receiving water bodies can be determined. This exercise must, therefore, include the identification of receiving water bodies and associated water users and uses. As part of the groundwater management process, the results from the hydrogeological investigation and numerical modelling exercise need to be demonstrated to the applicable Government Departments and interested and affected parties (I&AP's).

As mentioned previously the main indicator element, sulphate, will be applied to delineate the plumes. The calibrated area over which sulphate concentrations are expected to increase to above 200 mg/l SO_4 contour is subsequently used to delineate the plumes (or the selected water quality guideline for domestic/agricultural/industrial use). The area of an increase of 400, 600, 800 and 1000mg/l in sulphate also graphically illustrated and explained. This will enable scenario modelling, where the effect and feasibility of rehabilitation techniques, such as source rehabilitation and pathway interception, is simulated. Individual plumes are then mapped through GIS techniques. Each plume is classified and a specific identification is awarded.

The extent of each identified plume is expressed in terms of area (ha) and volume (m3). The volume of each plume is based on the area times the assumed depth of pollution times the porosity. The porosity is based on the average or combined porosity of the aquifer matrix, fractures, cavities, etc.

Combine All:

All identified variables in terms of source; pathway and receivers can now graphically be presented to enable a system for future management purposes (Figure 5.) GIS or any form of graphical interpretation can be applied. A summary excel spreadsheet or database system is usually very handy to keep track of all source entities and to start off with preliminary impact ratings per identified source/plume (refer to Table 3). This allows for a better understanding on which source entities to focus during the next steps of liability estimation. Table 3 lists variables that can be used for the process. Each aspect was rated out of a possible 10 points, 5 for the likelihood and 5 for the severity of the aspect. All aspects count out of a possible 100. If a total of >65 is obtained a high risk is allocated, a score of between 65 and 55, a medium risk and a score below 55, a low risk.

Once the calculations for diffuse seepage from individual pollution sources are completed, a percentage of contribution to individual plumes are awarded by simply dividing the potential mass flux from individual sources by the total contribution of all the sources in a specific plume area. Water balance data obtained from numerical model simulations needs to be translated into a salt balance for this purpose. This will ultimately provide input to the risk assessment on receiving water bodies in terms of salt load.

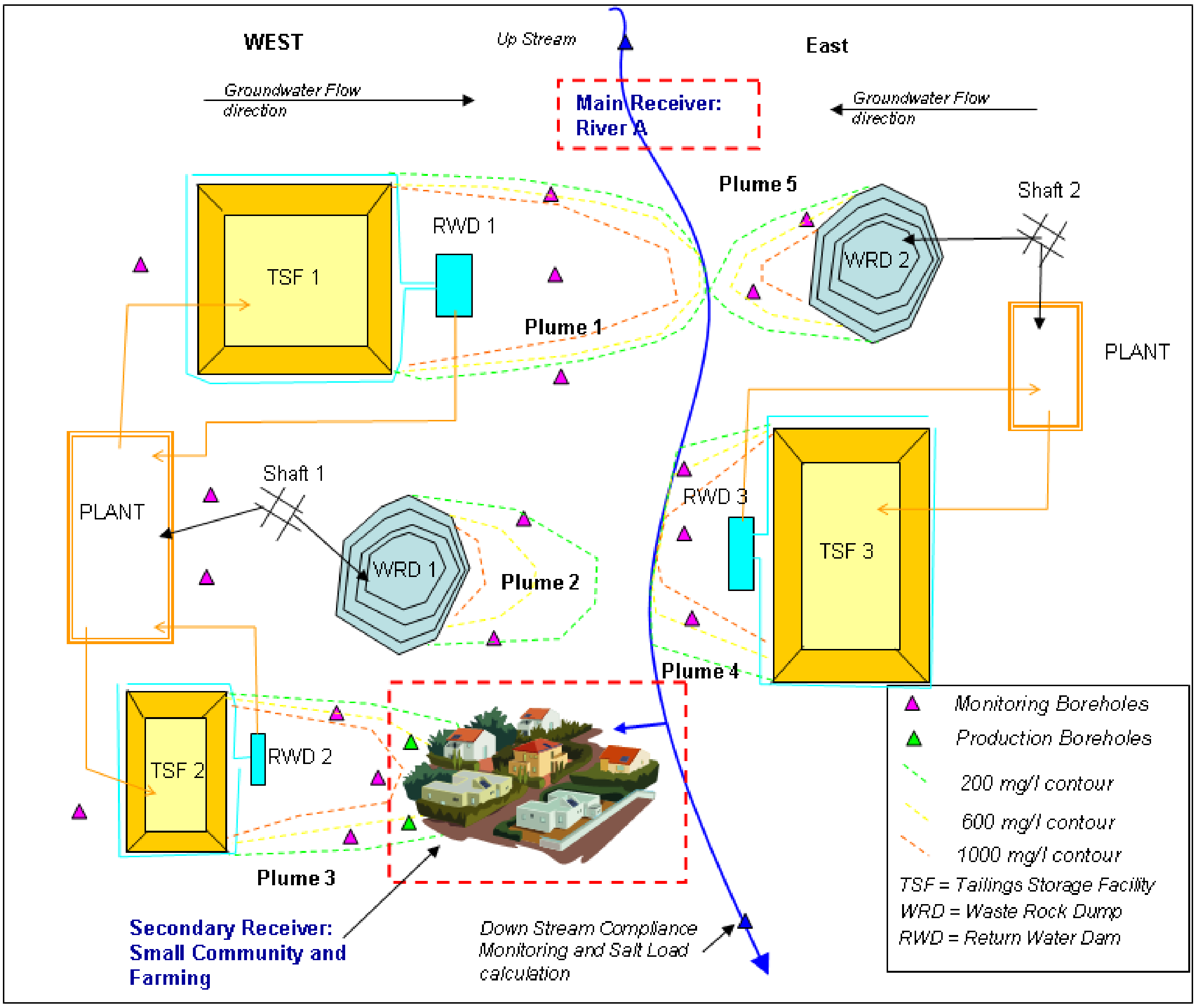

Figure 5. Typical plume delineation plan

Table 3. Example of preliminary impact rating

	Source	Approx Area (ha)	Responsible Person	Quantity of Waste			Leakage potential & Liner			Toxicity of leakage			Infiltration Potential (n)			Mass Transport (Pollution migration (K, T))			Depth to groundwater			Aquifer vulnerability			Downstream users/Receptor			Legislation & Compliance			Closure Implications			Total
AREA 1: West (Plume 1, 2 and 3)				L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	
1	TSF 1	155.6	a	5	5	10	5	5	10	4	4	8	4	4	8	5	5	10	5	5	10	5	5	10	5	5	10	4	4	8	5	5	10	94
2	TSF 2	166.2	a	4.5	4	8.5	5	5	10	4	4	8	4	4	8	5	4	9	4	4	8	4	4	8	4	4	8	4	4	8	5	5	10	85.5
3	Return Water Dam 1	17.0	b	3	5	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	80
4	Return Water Dam 2	9.0	b	3	5	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	80
5	WRD 1	25.0	c	3	3	6	3	3	6	3	3	6	3	3	6	3	3	6	3	3	6	3	3	6	3	3	6	3	3	6	3	3	6	60
7	Ore loading area 1	2.0	c	2	2	4	3	3	6	3	3	6	3	3	6	3	2	5	2	2	4	3	3	6	2	2	4	2	2	4	2	2	4	49
8	Sewage Plant	2.0	d	2	2	4	2	2	4	3	3	6	2	2	4	2	2	4	4	4	8	2	2	4	2	2	4	2	2	4	2	2	4	46
																																	AREA TOTAL RISK:	71
	AREA West = High Risk																																	
	Source	Approx Area (ha)	Responsible Person	Quantity of Waste			Leakage potential & Liner			Toxicity of leakage			Infiltration Potential (n)			Mass Transport (Pollution migration (K, T))			Depth to groundwater			Aquifer vulnerability			Downstream users/Receptor			Legislation & Compliance			Closure Implications			Total
AREA : East (Plume 4 and 5)				L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	
1	TSFCompartment 1	152.0	a	4	3	7	3.5	5	8.5	3.5	4	7.5	3	4	7	3	4	7	3	4	7	3	3	6	2.5	2.5	5	3	3	6	5	5	10	71
4	Return Water Dam1	3.0	b	2	2	4	3	3	6	4	4	8	3	3	6	2	2	4	3	3	6	3	3	6	2.5	2	4.5	3	3	6	3	3	6	56.5
6	WRD 2	7.0	c	3	3	6	3	3	6	3	3	6	3	3	6	2	2	4	3	3	6	3	3	6	2.5	2	4.5	3	3	6	2	2	4	54.5
7	Sewage Plant 2	7.0	d	3	3	6	3	3	6	3	3	6	3	3	6	2	2	4	3	3	6	3	3	6	2.5	2	4.5	3	3	6	2	2	4	54.5
																																	AREA TOTAL RISK:	59
	AREA East = Medium Risk																																	
	(L = Likelihood, S = Severity, T = Total)																																	

5. FINANCIAL MODEL

Mine closure planning and liability assessments are critical components of the strategic planning process of each mine. Uncertainties with regards to the legal requirements, standards and benchmarks, time aspects, environmental impacts, cost, etc. are all factors currently hampering closure planning.

The financial modelling exercise is undertaken to identify costs associated with each management option, as well as pros and cons of the following.

1.) Rehabilitation Technologies. All possible groundwater rehabilitation methods must be identified and a cost estimate per unit must be established. <u>It is very important to focus on source rehabilitation and then on pathway interception</u>. It is, however, very important to not waste time on methods that would be difficult to apply in site-specific geological and geohydrological conditions, rather focus on 2 to 3 methods that should work.

2.) "Soft Issues". These include issues which are uncontrollable and which could significantly or potentially impact on the final liability figures. An example could be civil claims from I&AP's (interested and affected parties), and so forth. It is usually very difficult to apply a cost to this.

3.) Legal Compliance – currently the main driver in South Africa could be aspects like; the Waste Discharge Charge System (WDCS), other directives from DWA (Department of Water Affairs), closure constraints and ongoing monitoring, etc.

The Financial models must subsequently be incorporated into the risk rating exercise to establish a figure for current and future groundwater liabilities.

6. FINAL LIABILITY ESTIMATION

When considering the flow diagram (Figure 1) and the approach presented in this paper, it can be seen that the three primary aspects (Source, Pathway and Receiver) are now better understood for the case study. The technical aspects can now be translated into costs, legal compliance and environmental risks. This can be seen as the total *liability* for a given source. The approach will further focus on the following:

- 80/20 Principle: The principle of focussing on the more significant groundwater issues initially. All sources, pathways and receivers are listed and assessed. The contamination plumes which have, and will after closure have a more significant impact on receiving water bodies must receive more time and resources as part of the groundwater management programme developed for the project. The completed impact rating table serves as a guideline for this approach. The 80/20 principle was adopted and applied; this means that 20% of the sites, which cause 80% of the pollution, will be classified as "problem areas" and will receive priority attention.
- Assumptions: In the absence of reliable data, consciously conservative assumptions must be made and applied during model application and for cost estimations. This must be achieved without jeopardizing the value of the model or determination of liabilities.
- Hydrogeological Site Assessment (HSA): It is critical that the site assessment be based on a risk based approach or the environmental risk assessment (ERA) process. The HSA will be applied during the determination of groundwater liabilities and should pursue a consistent and structured process. The basic principle incorporated into the proposed approach is that the level of detail of the HSA should be appropriate to the risks that exist. That means that minor risks need not be subjected to a detailed quantitative risk assessment process, while significant risks should be assessed beyond a simple qualitative assessment (refer to 80/20 principle).
- Remediation Techniques: Costs associated with each remediation option must be estimated, under the guidance of engineers and consultants within their various areas of expertise. The principle of best available technique which could be adapted to site-specific requirements, and which could be applied to be sustainable, needs to be considered throughout the finical estimations.
- Legislation: Consideration must also be given to existing policy documents by governmental departments.

The *liability* is therefore based on the diffuse seepage from the sources and the fate of end receivers like streams, rivers, regional aquifers, groundwater users, surface seepage, etc. This liability is accordingly defined in terms of capital and operational expenditure (financial terms) for appropriate groundwater management options. These are forecasted by applying the numerical model and scenario modelling.

For Example in the Case Study:

Short term shallow seepage interceptions will be applied for TSF 3 (refer to Figure 5) through the application of a 3 m depth trench; the capital cost and operational costs for 8 years can be calculated. This includes 4 years during operations and 4 years after closure. The TSF will be rehabilitated to minimise recharge from rainfall. A block of trees will be planted between the river and the TSF in the 4th year to handle the long-term remaining seepages. The plantation will be managed for 14 years post-closure.

Similar techniques, as discussed in this paper, will be applied to all the other plumes identified to facilitate the calculation of capital and operational costs.

Quarterly water monitoring will continue for 2 years after closure and bi-annually for the next 10 years. The aim is to identify the improvement stages of groundwater quality and plan the final stages of post-closure and final closure application.

7. CONTINUOUS REFINING OF LIABILITY ESTIMATES

A process of annual evaluation, information gap analyses, field work, assessments, sensitivity analyses and calibration needs to be incorporated within the process. There should be a list of critical identified aspects that need more data, clarification and/or field investigations. This includes the main "uncertainties" which comprises other aspects that usually require more attention. A more compressive scientific approach and analysis could therefore be required.

When the baseline Liability Estimation is completed, different "After Land-Use" applications must be incorporated so that an indication of risk and effect can be obtained. A detailed health risk assessment should be part of the long-term land use determination exercise. It is important that both soil and vegetation be incorporated into such an assessment. The reason for the proposed combination of soils and vegetation with groundwater is due to the occurrence of abnormal shallow perched aquifers, which contain high concentrations of salts and which are interconnected with deeper aquifers. The interaction between these disciplines should be investigated in more detail.

8. CONCLUSIONS, RECOMMENDATIONS & STRATEGIC GROUNDWATER MANAGEMENT CONCEPT

The main objective of this paper was to illustrate a logical approach towards Groundwater Liability Estimations, Mine Closure Planning and Remediation regarding the Hydrogeological environment. The need for groundwater assessments during the operational phase of mining and later during the de-commissioning phase was highlighted. The main driving force behind this paper was, therefore, to explain the steps that need to be followed to achieve the technical (scientific based) hydrogeological end-results. The end results, in turn, should then be evaluated to achieve the main objective which can be translated into the following:

1. Data collection phase: The first and most important step is to obtain all available and updated groundwater monitoring data. Time series data forms the basis of flow and transport simulations during the numerical modelling phase.

   Other important information sets that are essential for the assessment include:

   i. Geological data – to enable a geological conceptual model for the area in terms of different stratigraphical layers, degree of weathering and fracturing, structural geology, etc.

   ii. Geohydrological data – aquifer mechanics, flow directions and gradients, recharge, hydro-chemical and geochemical behaviour, etc.

   iii. Site specific information in terms of surface and underground mining infrastructure that holds the potential to impact on the local aquifer systems in terms of quality and/or quantity. This mainly includes:
      a) Tailings storage facilities (TSFs),
      b) Return water and/or pollution control dams,
      c) Earth trenches,
      d) Metallurgical plants,
      e) Waste rock dumps,
      f) Other waste storage facilities, and
      g) Historical dumping/spillage areas.

2. Conceptual Site Model: All the available data is then combined and populated to construct hydrogeological and geological conceptual models of the different areas.

3. Numerical modelling: The conceptual site model data is subsequently applied into a three-dimensional MODFLOW groundwater model. The flow model is firstly calibrated through time series water level data and secondly the mass transport model through time series hydro-chemical data.

4. Risk/Impact Rating: Apply a GIS system to combine all information and to assess the relevant risks/impacts in terms of financial, legal and environmental aspects.
5. Groundwater Management and Liability Estimation: The last step in the assessment is to do a detailed interpretation of all constructed mass transport plumes. Different management options are proposed to either intercept the plumes at the source and/or within the pathway just before the source. All applicable financial implications are then determined.

9. SOME USEFUL REFERENCES

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